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ASSESSMENT
OF PHYSICAL CAPABILITIES

With special reference to the evaluation
of maximal voluntary isometric muscle strength
and maximal working capacity

An experimental study on civilian and military
subject groups.

BY

GUNNAR TORNVALL

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Introduction

Determination of physical fitness is a valuable adjunct to other examinations in appraisal of healthy as well as diseased individuals. By estimation of the physical capacity, a rational selection of personnel for various occupations in, for example, industry and military service may be facilitated. In medical rehabilitation also, establishment of the physical state is important, since it provides the basis for correct diagnosis, for therapy evaluation and prognosis.

In determining physical fitness, several components may be taken into consideration, i.e. strength, velocity, precision and endurance. Different forms of physical activity will make their specific demands on these qualities. Among abilities used in heavy physical work, however, muscle strength and endurance may be considered to play a dominating role.

During the last few decades, technical progress has involved a successive decrease of physical activity for large parts of the population. The consequent lowering of the training level implies a reduced preparedness for emergency situations on the part of both individuals and the State. A reaction against these tendencies has been evoked among military as well as medical authorities. The interest in these problems has initiated physiological investigations in large civilian and military groups. These investigations, performed during the last few years, have *inter alia* included determination of physical working capacity, muscular strength and various constitutional factors (56, 92). In this connection, new points of view have been presented regarding the relation between these different qualities in different subject groups and under different conditions. As a continuation of these studies a further elucidation of the methods for assessment of physical fitness in military personnel has been proposed.

In the present work the purpose has been to study some problems involved in determination of muscular strength and physical working capacity. Among questions to be elucidated the following may be mentioned.

1. Biological and methodological variability in evaluation of maximal voluntary isometric muscle strength.
2. Interrelationship between muscle-strength values recorded in different parts of the body.
3. Average muscular and circulatory changes during basic military service.
4. Relationship between work load and duration in maximal physical performances.
5. Reproducibility of an index of maximal working capacity.
6. Circulatory adaptation during maximal physical work.
7. Association between expressions for maximal working capacity on the one hand and muscular and circulatory capacity factors on the other.

PART I

General

Methods

For characterization of the material as well as for studies of the relationship between different physiological data a number of investigational techniques were used.

Clinical examination

Each subject was interviewed according to a standard questionnaire. Information was collected regarding age, place of residence, civil occupation and participation in sport activities. The history of previous illness was taken and current symptoms asked about with special regard to cardio-pulmonary diseases and acute catarrhal infections. The general condition of the subject was noted and physical examination of the heart was performed. The systolic and diastolic blood pressure was measured with the aid of a mercury manometer on the right arm, diastolic pressure being read at disappearance of Korotkow sounds. Only if specially indicated were other organ systems included in the examination. This health control was performed by colleagues working in the Military Medical Centre.

Anthropometric determinations

Evaluation of various constitutional factors was made according to the principles and methods described by Martin, Stolz & Stolz and Lindegård (88, 94, 122). Some minor modifications were, however, introduced.

The body height was measured to the nearest 0.5 cm with the subjects barefooted. The individuals stood with the back of the head against the rule. As another expression of skeletal length the size of the tibia was determined. The measurement of bone length was performed externally with the aid of an anthropometer and the value recorded in millimetres. For the tibia the length was measured between the margin bordering on the tibial-femoral articular groove and the distal end of the medial malleolus.

For evaluation of skeletal sturdiness the femoral condylar breadth was determined with a special instrument, graded in 0.1 mm (56). The femoral condylar breadth was here defined as the linear distance between the medial and lateral surfaces of the condyles. The subject was examined in the sitting

position with the knee joints at 90°. The calipers were slightly pressed against the condyles and the instrument held perpendicularly to the long axis of the leg.

The skeletal measures were taken only on the right-hand side, since comparison of right- and left-side values had shown only minor differences. For the femoral condyles the left-side dimensions were smaller than the right-side values by about 0.5 % (*diff.* 0.05 cm *P****). For tibia length no significant difference was found between the right and the left side.

The amount of fat was estimated by measurement of the skinfold thickness according to Keys & Brozek (82). The regions used were (1) on the back, immediately caudally to the scapula, (2) at the axillary border of the pectoralis major muscle at the level of the mamillae, (3) on the abdomen in the midclavicular line at the umbilical level.

The body weight was measured with the individuals wearing shorts, the values being recorded to the nearest 0.1 kg.

Laboratory investigations

Roentgenological determination of heart volume

The heart volume was determined according to the method of Larsson & Kjellberg as modified by Kjellberg *et al.* (83, 85). The individuals were here investigated in the prone position. Calculation of the heart volume was made from two roentgenograms taken simultaneously in the lateral and anterioposterior projections. No consideration was paid to the phase of the heart contraction or the respiratory cycle. In the technique mentioned, the X-ray tube is angled 30 degrees caudally. As has been shown by Heilborn & Strandell, this procedure may induce a systematic error, leading to an overestimation of the heart volume, especially in individuals with large thoracic dimensions (54). In the present subject groups, consisting mostly of young men of ordinary slim build, this error may be relatively small. In a series of duplicate determinations on conscripts ($n = 43$) the error of a single determination amounted to 44 ml (3.9 % of the mean value).

Determination of total haemoglobin (THb) and blood volume (TBV)

The total amount of haemoglobin was determined by the alveolar carbon monoxide method as described by Sjöstrand and coworkers (90, 115). As a rule, duplicate determinations were performed at intervals of less than one week. As normal values for adult males, 11–12 g per kg body weight have been reported by Holmgren *et al.* (68). In the present investigation the standard error of a single determination was found to be 3.7 %.

The haemoglobin concentration was determined spectrophotometrically after haemolysis with ammonium solution, duplicate samples of finger blood being used.

The total blood volume was calculated from the total amount of haemoglobin and the relative haemoglobin concentration. The slight error due to the assumption of a constant haemoglobin concentration in the whole blood was disregarded. The mean value found for adult males is here 82 ml per kg body weight, according to Holmgren *et al.* (68).

Determination of lactic-acid concentration

A capillary sample was taken from the finger tip after heating with towels soaked in hot water. Special care was taken to avoid any admixture of sweat or other contaminating agents to the sample. The blood was analysed according to the method of Barker & Summerson with slight modifications (described in ref. 67). Here 0.05 ml of blood was pipetted into 4 ml trichloroacetic acid. After centrifugation of the precipitate the lactic acid was oxidized by concentrated sulphuric acid. The acetaldehyde formed was determined colorimetrically through the reaction with p-hydroxydiphenyl in the presence of cupric ions. In the material investigated by Holmgren the error of a single determination amounted to 3.5 % (67).

Evaluation of isometric muscle strength

See page 21.

Assessment of physical working capacity

See page 61.

Statistical methods

The data were treated according to current statistical methods.

Random selection was performed with the aid of random digit tables (131). For calculation of the significance of differences and of correlation coefficients the *t*-test was used. If the probability of the findings being due to chance was less than 0.1 per cent ($P = < 0.001^{***}$), it was regarded as highly significant; if it was less than 1 per cent but equal to or greater than 0.1 per cent ($P = 0.001-0.01^{**}$) it was denoted as significant; if it was

less than 5 per cent but equal to or greater than 1 per cent ($P = 0.01-0.05^*$), it was regarded as probably significant. For studies of correlation by regression analysis the methods described by, e.g., Snedecor were employed (120).

Statistical symbols

n = number of observations	r = correlation coefficient
$\bar{x}$ = arithmetic mean	s_e = deviation of residuals in linear regression
s = standard deviation	$diff.$ = difference between two means
$s_{\bar{x}}$ = standard error of the mean	p = probability
V_{coeff} = coefficient of variation	

Material

Different military as well as civilian subject groups were investigated. To get representative values the individuals were if possible chosen at random from larger populations. In some instances, where this could not be done, the subjects were chosen in such a manner as to give at least a rough cross section of the actual population. The military personnel was as a rule ordered to undergo the examinations. In one group, however, where the investigation was part of a selection procedure for special service, all examinees were volunteers.

Military personnel

The numerically predominant group of personnel in the Swedish Defence System consists of civilian subjects performing their compulsory military service. The present investigations were confined to subject groups from this category of national servicemen. Before the investigation at the Military Medical Centre these men had all passed two health controls, i.e. at registration and at induction, pathological cases having then been rejected. The resulting selectivity accounts for the subsequent paucity of pathological findings.

Only in one case did a suspected pathological Ecg motivate exclusion of the subject. Slight respiratory infections were relatively common; in such cases the investigation could as a rule be postponed until the subject had recovered, usually after a week. In some instances, however, more prolonged infections, fractures or other injuries disqualified the subject from continued participation in longitudinal studies.

The investigations were consequently concerned only with normal healthy persons, normality being defined as absence of abnormal subjective symptoms and objective signs in the examination performed.

Series A

From a population of about 700 fully fit conscripts assigned to an infantry regiment in Stockholm (I 1), 100 men were drawn. The selection was performed on the basis of random digit tables. Of the individuals selected, 89 were investigated during the first two weeks after induction in May—June

960. Some of the subjects participated in further examinations during the period of basic military training (nine months). The subject group was used mainly for elaborating and testing the method for muscle-strength evaluation. Some of the main characteristics of the series are reported below.

Series B

From a contingent of about 700 fully fit conscripts called up for military service in the spring of 1961 100 men were selected at random. They belonged to the same regiment as the above-mentioned group, and in all essential respects they were similar to that material. At the first examination, shortly after induction, 93 individuals who were available underwent anthropometric classification and physical fitness assessment. Thereafter the examinees were the subject of a follow-up study throughout the nine months of basic military training. The protracted investigation involved a further reduction of the original material. Among the reasons for exclusion were the following: deferment of military service, removal to other regiments, accidental illness at the time of one or several examinations or changed classification as regards military fitness group. One condition for inclusion in the study was that the subjects should be fully fit for military service and that they should have taken part in the regular training during the whole period of investigation. The characteristics of the original series (B) are compared with those of the remaining group (B₁). All data refer to the examination in May—June 1961. (See Table 1.)

Series C

Fifty-eight conscripts fully fit for military service were drawn from a coast artillery regiment in the vicinity of Stockholm (KA 1). The selection of this group could not be performed at random, and the results may therefore not strictly represent the population mentioned. As far as could be judged from anthropometric data, however, the subjects did not differ appreciably from average conscripts as regards body build, comparison with series A and B showing no statistical difference in this respect. Nor did the physical working capacity (PWC₁₇₀) show any great difference from that generally found at the stage of military training in question, i.e. four months after induction. The examinations were performed in April 1961. Some of the main characteristics of this subject group appear from Table 1.

Series D

Fifty-two conscripts from the same coast artillery regiment as the above-mentioned group were ordered to undergo investigation in February 1962,

Table 1. Mean data of investigated subject groups

	A	B	C	D	E	F	G	G _L
	Conscripts investig. in 1960 ¹	Conscripts investig. in 1961 ¹	Conscripts investig. in 1961 ¹	Conscripts investig. in 1962 ¹	Conscripts investig. in 1962 ¹	Civilian volunteers	Middle distance runners	Weight lifters
Number.....	89	93	58	52	36	28	9	15
Age, years	$\bar{x}$ 19.5 s 0.5	19.6 0.5	19.6 0.5	20.3 1.0	20.3 1.0	26.2 5.4	28.4 6.1	27.1 5.5
Occupation								
heavy	% 16.9	% 18.3	% 13.8	% 7.7	% 7.9	% 3.6	% 0	% 8.7
intermediate	% 14.6	% 30.1	% 37.9	% 26.9	% 44.7	% 7.1	% 22.2	% 30.4
easy	% 22.5	% 20.4	% 19.0	% 25.0	% 21.1	% 39.3	% 44.5	% 17.4
sedentary	% 46.0	% 31.2	% 29.3	% 32.1	% 26.3	% 50.0	% 33.3	% 43.5
Residency								
Stockholm area	% 77.8	% 71.0	% 70.7	% 44.6	% 21.1	% 100	% 100	% 73.9
other towns	% 8.9	% 8.6	% 10.3	% 32.2	% 60.5	—	—	% 4.3
rural	% 13.3	% 20.4	% 19.0	% 23.2	% 18.4	—	—	% 21.8
Sport								
competition	% 26.7	% 30.1	% 27.6	% 8.9	% 50.0	% 21.4	% 22.2	% 100
exercise	% 25.6	% 21.5	% 22.4	% 28.6	% 42.1	% 25.0	% 22.2	—
no sport	% 47.7	% 48.4	% 50.0	% 62.5	% 15.7	% 53.6	% 55.6	—
Height cm	$\bar{x}$ 178.2 s 6.8	177.8 6.2	178.4 6.4	179.4 6.4	178.7 5.7	179.6 6.7	178.8 8.4	172.2 5.3
Weight kg	$\bar{x}$ 68.3 s 8.6	66.5 7.4	67.3 7.7	69.6 7.0	70.9 7.3	73.5 8.9	73.4 11.9	78.8 12.1
Fem. cond. breadth mm	$\bar{x}$ 9.8 s 0.5	9.8 0.4	9.9 0.4	9.8 0.4	—	10.0 0.4	10.2 0.5	9.9 0.3
Length of tibia cm	$\bar{x}$ 40.3 s 2.3	40.2 2.2	40.6 2.2	40.4 2.3	—	40.4 2.6	40.2 2.7	38.1 2.4
Skinfold thickness								
region I: mm	$\bar{x}$ 8.0 s 3.0	7.8 2.6	7.9 2.6	7.8 2.0	—	9.4 4.0	9.4 5.3	9.1 1.2
PWC ₁₇₀ kpm/min	1,064 218	1,038 194	1,058 199	1,140 158	—	1,086 167	1,092 135	1,177 211
PWC _{max} 6' kpm/min	$\bar{x}$ — s —	— —	— —	1,427 180	1,474 150	1,513 220	1,466 213	— —
Heart volume ml	$\bar{x}$ 792 s 129	766 106	770 104	783 88	805 109	—	—	869 144
Muscle strength kp								
Handgrip right	$\bar{x}$ 68.2 s 11.0	66.5 10.0	66.6 8.5	68.6 10.3	—	70.1 10.9	70.1 11.3	80.0 9.9
Elbow fl. *	$\bar{x}$ 29.4 s 4.3	28.3 3.6	28.2 3.5	30.5 4.0	—	29.6 3.2	30.3 4.1	37.7 3.8
Knee ext. *	$\bar{x}$ 53.1 s 12.3	50.0 8.5	50.6 8.6	49.7 8.6	—	50.9 7.7	47.3 6.9	74.4 10.5

Note: In certain examinations only part of the subject groups participated. The reduced number of individuals will in what follows be noted in each case.

* Selected at random from an infantry regiment (I 1). * Non-selected group from a coast artillery regiment (KA 1). * Navy men participating in an aptitude examination for submarine service.

about one month after induction. No systematic random selection was performed, but a cross section of physically fully fit conscripts belonging to the regiment was aimed at. Here too, however, a good correspondence was obtained for anthropometric data compared with other material selected at random. In this group of subjects studies on the maximal physical working capacity were made. See Table 1.

Series E

For a study of the reproducibility of maximal dynamic work at different loads a group of 36 men from the Navy was used. The investigation was performed in February 1962 at a time when the subjects had participated in military training for about one month. They had all volunteered for the study, and the investigation was part of an aptitude examination for submarine service. Consequently their motivation and physical data may not be representative of Navy men in general.

Civilian subject groups

Series F

Twenty-eight male individuals, including students, colleagues and personnel of the Military Medical Centre, volunteered in a series of investigations. This subject group was more heterogeneous than the military material as regards age and occupation, as well as training status. On the other hand they were available for longer and more complicated examinations. Evaluation of isometric muscle strength and determination of physical working capacity were performed. In some cases, however, maximal oxygen uptake was also measured. This part of the group was denoted as F₁.

Series G

Two groups of athletes, i.e. middle distance runners and weight lifters, were studied. The reason for choosing representatives of these branches of sport was a desire to elucidate the muscular and circulatory effects of one-sided physical training. The individuals were all taking part in competition activities. They belonged to the élite or the category just below that. The weight lifters formed a group of 15 men who had engaged in their specialty for an average of 7 years. Eight were referable to the heavyweight, two to the middleweight and five to the lightweight category. The other group consisted of 23 runners. They competed over distances ranging from 800 to 10,000 metres and the average period of competitive activity amounted to 4.5 years. The characteristics of Series G appear in Table 1.

PART II

Evaluation of muscle strength

Earlier investigations

The desire for objective methods in evaluation of muscle strength has generated an abundance of devices and techniques. A comprehensive survey of earlier work in this field is given by Hunsicker and Donelly (77). In this chapter only some of the main principles and methods will be mentioned.

Muscle force may be measured either isotonically or isometrically. Methods for isotonic determination are described by Mosso, Hellebrandt and DeLorme *et al.* (41, 55, 98). Here the force is measured during the whole range of movement effected by the muscle group in question. The procedure is tiring for the individual being tested, however, and in fact it is the work performed rather than the strength that is measured. Because of these disadvantages most investigators have resorted to some form of isometric testing. The force is then measured during isometric or almost isometric contractions in certain well-defined positions.

In isometric testing the following measuring techniques have been used: (a) manual methods, (b) mechanical spring balance methods, (c) the cable-tension method, (d) the mercurial-hydraulic method, (e) pneumatic systems, and (f) strain-gauge methods.

Most dynamometers have been constructed for determination of the finger flexion force. This is the case with the early mechanical balance dynamometers of Régnier, Burq, Duchenne, Brigham, Mathieu, Collin, Smedley and Duvall *et al.* (27, 42, 77, 119).

Pneumatic systems have been used by Hamilton and Geckler, whereas Tuttle *et al.* have more recently devised a hand dynamometer according to the strain-gauge principle (48, 51, 127). For testing the arm and back muscles a modification of the hand dynamometer of Régnier has been used. Other spring balance instruments have been constructed by Sargent, Vernon and Tuttle *et al.* for the back and leg, by Shochrin for the leg and by Haxton and Lindegård *et al.* for the plantar flexion (53, 89, 111, 113, 126, 132).

Arm dynamometers have been devised by Galton, using mechanical springs, and by Darcus, Bonde-Pedersen and Ralston *et al.*, applying the strain-gauge principle (22, 39, 47, 107).

For a more extensive testing of muscle strength several different systems are available. As early as in 1893 Kellogg described a universal dynamometer, where the force of 22 muscle groups could be recorded with the aid of a

hydraulic system with mercury (81). Lovett *et al.* have devised a method, by which instead of the concentric and isometric force the eccentric force of different muscles is measured (93). In this so-called "break method" is determined the power with which a person can resist an externally applied force. In connection with this technique, simple spring balances or more complicated dynamometers according to the modification of Schmiedeberg have been used (112). A cable-tension method has been developed by Clarke and coworkers. In this the force exerted is transmitted by straps and cables to the tension-sensitive unit. For fixation and standardization of positions a special table and stand enable the cables to be fixed in the desired angles according to the muscle group to be tested. The individuals are investigated in the horizontal position, and assistants are used to ensure fixation (31).

The perfecting of strain-gauge instruments during the last decade has initiated a wider application of this technique in muscle testing. In the experimental equipment of Beasley two alternative strain-gauge dynamometers are used, a so-called manual-force gauge and an axial tensiometer gauge. For testing with the latter a system of cables and mechanical couplings is used in a way similar to that in the method of Clarke (17). Another apparatus using strain gauges has been described by Asmussen *et al.* (4). In this method the strength in different muscle groups is measured by a number of dynamometers connected to a central recording instrument. As this arrangement was found convenient for the purposes of the present investigation, equipment similar to the Danish apparatus was chosen. Certain modifications of the strain-gauge system as well as the fixation arrangements were, however, found desirable.

Method

Principle

The strength in different muscle groups was measured during almost isometric contractions. The person investigated had to make "attempted movements" in standardized positions. The force developed was measured with the aid of special dynamometers.

Apparatus

For standardization of positions and for fixation of the subject a special chair was designed. The dimensions of the seat and of movable arm and leg supports could be adjusted to the size of the individual. Furthermore, dynamometers attached to the chair could be placed in positions corresponding to certain anatomical points.

The dynamometers consisted of elastic steel rods to which strain gauges were glued. For temperature compensation one strain gauge was placed on each side of the rod. The dimension of the steel rod was chosen according to the measuring range desired for each dynamometer. The effective lever of the rod could easily be varied for the purpose of calibration. By means of straps or other connections the force of the contracting muscle group was transmitted to the steel. At the resulting deformation the electrical resistance of the strain gauges was changed. This change was measured by a central recording instrument consisting of a Wheatstone's bridge coupled to an alternating current amplifier.¹ Before every testing phase the appropriate dynamometer was connected to the measuring bridge with the aid of a special unit.²

The capacitance and resistance of the electrical circuit were furthermore adjusted in order to place the pointer of the scale at the initial zero level. The forces measured were read directly in kiloponds according to prior calibration.

The separate dynamometers had different designs, depending upon the

¹ Measuring bridge KWS 11/5 0—1,500 Hz Hottinger.

² Measuring-unit selector UD 6 Hottinger.

Note. The instrumental equipment was designed in cooperation with K.-H. Mattson and B. Widén, Institution of Theory and Design of Electrical Machinery, Royal Institute of Technology, Stockholm.

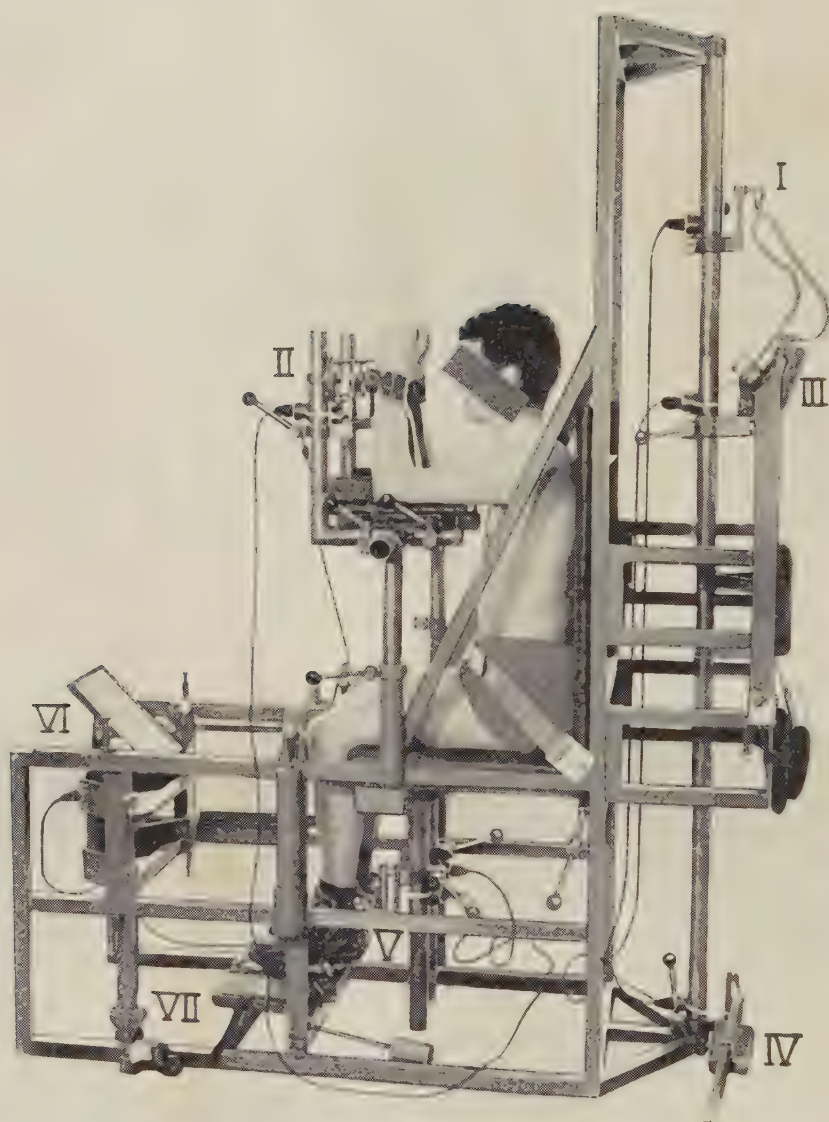


Fig. 1. Apparatus for muscle-strength determination

<i>Dynamometer</i>	<i>Application</i>
No. I	neck flexion and extension
II A and B	elbow flexion and extension
III	trunk, flexion forwards and backwards
IV	hip and knee flexion
V A and B	knee extension
VI	leg extension
VII	foot dorsal and plantar flexion

demands of the testing situation. Some of them could, however, be used for strength determination of several muscle groups. The technical equipment and testing procedure are shown in Figs. 1 and 2.

Procedure

(1) General

The person was instructed to perform maximal attempted movements in appropriate positions, striving to avoid jerks and other trick movements. After the maximal level of contraction had been reached it had to be held for about two or three seconds, allowing the investigator to read the value on the potentiometer scale. Every attempted movement was performed three times with intervals of about 15—20 seconds. If the highest value was reached the third time, additional contractions were requested, until the maximum of the series was obtained. The highest value was used as an expression of the maximal contractile force. Each moment of testing was preceded by thorough instruction and demonstration of the attempted movements wanted. In what follows the standardized positions, fixations and dynamometer types used are described for each movement. The principal muscles which are mechanically capable of acting in the test movements used are also listed according to current anatomical and physiological literature (5, 65, 108).

(2) Description of the muscle test

Neck

FORWARD FLEXION OF THE NECK (Flexion)

Dynamometer No. I

The individual was investigated in the standing position. The *dynamometer* with its leather strap was placed horizontally at a level of about 2 cm above the eyebrows of the individual, clasping his forehead.

Participating muscles: m. sternocleidomastoideus, m. rectus capitis ventralis et lateralis, mm. scaleni, mm. longus colli et capitis, platysma, the hyoid muscles, when the mandible is fixed by its elevators.

BACKWARD FLEXION OF THE NECK (Extension)

The same *dynamometer* and arrangement were used as for forward flexion. The strap was, however, now placed horizontally around the back of the head, with the individual facing the *dynamometer*.

Participating muscles: m. trapezius, mm. rectus capitis dorsalis major et

minor, m. obliquus capitis, m. obliquus atlantis, m. splenius, m. longissimus cervicis et capitis, m. transverso-occipitalis, mm. transversocostales, mm. interspinales cervicis.

Trunk

FORWARD FLEXION OF THE TRUNK

Dynamometer No. III

With the individual in the standing position the *dynamometer* was placed with its strap around the chest at a level corresponding to the midpoint of the sternum. The subject was then instructed to take support with the lower part of the back against a padded plate and to bend forward (see Fig. 2 a).

Participating muscles: m. rectus abdominis, mm. obliquus abdominis externus et internus, m. pyramidalis, m. rectus femoris, m. ileopsoas, other hip flexors.

BACKWARD FLEXION OF THE TRUNK

The *dynamometer* was the same as for forward flexion, but the individual now had to face the measuring unit. Support was taken with the pelvis against the plate and the trunk was bent backwards against the *dynamometer* strap.

Participating muscles: m. sacrospinalis, mm. interspinales, m. spinalis, m. semispinalis, mm. multifidi.

Arm

SHOULDER PULL

Dynamometer No. VIII (see Fig. 2 c)

The individual was tested in the standing position. He was instructed to keep the *dynamometer* in front of the jugular notch and to try to pull the handles apart.

Participating muscles: m. triceps brachii, m. deltoideus, mm. teres major et minor, mm. rhomboides major et minor, m. trapezius, m. latissimus dorsi.

FLEXION OF THE ELBOW

Bilateral testing

Dynamometers Nos. II A and B

The individual was examined sitting in the chair. By means of arm supports the upper arms were held horizontally in front of the shoulders at right angles to the trunk. The elbow also was held at 90° with the forearm vertically in a

position between pronation and supination. The fastening strap of the *dynamometer* was placed at the level of the styloid process of the radius.

Participating muscles: m. biceps brachii, m. brachioradialis, m. brachialis, m. pronator teres, m. flexor carpi radialis, m. palmaris longus, m. flexor digitorum superficialis, m. flexor pollicis longus, m. extensor carpi radialis longus, m. flexor carpi ulnaris.

EXTENSION OF THE ELBOW

Bilateral testing

Dynamometer and positions were the same as for elbow flexion. To secure a standard position of 90° flexion in the elbow the upper arm was fixed manually by the assistant. At attempted extension the pressure of the wrist was transmitted to the steel rod by a padded plate.

Participating muscles: m. triceps brachii, m. anconaeus.

FINGER FLEXION

Bilateral testing of handgrip

Dynamometer No. VIII (see Fig. 2 b)

The person was tested in the standing position. The handle distance of the *dynamometer* was adjusted to the size of the subject's hand. The upper arm was held vertically and the elbow was flexed at 90°. The *dynamometer* was supported by the hand not being tested.

Participating muscles: m. flexor digitorum superficialis, m. flexor digitorum profundus, mm. flexor pollicis longus et brevis, m. opponens pollicis, m. adductor pollicis, mm. interossei, mm. lumbricales.

Leg

FLEXION OF THE HIP

Bilateral testing

Dynamometer No. IV

The subject was investigated in the standing position with the back against a padded support. The *dynamometer* with its strap was placed at a level immediately above the patella. The subject was instructed to keep the trunk fixed against the support and to flex the hip, keeping both knees extended (see Fig. 2 f).

Participating muscles: m. ileopsoas, m. rectus femoris, m. tensor fasciae latae, m. sartorius, m. gracilis, m. pectineus, mm. adductores, m. obturator ext., mm. gluteus medius et minimus, m. quadratus femoris.

LEG EXTENSION

Combined movement, where the composite force of both legs was measured.

Dynamometer No. VI

The measurement was performed with the subject sitting in the chair with his feet on the plate connected to a strain-gauge unit. By adjusting the *dynamometer* back and forth it could be fixed in a position such that the angle between the femur and the tibia was about 150°. The subject was instructed to take support with the sacrum against the back of the chair and to press the footboard forward (see Fig. 2 d).

Participating muscles: mm. gluteus maximus, medius et minimus, m. semitendineus, m. semimembraneus, m. biceps femoris, m. quadriceps femoris, m. adductor magnus, m. obturator int., m. piriformis, m. rectus femoris, m. tensor fasciae latae.

FLEXION OF THE KNEE

Bilateral testing

Dynamometer No. IV.

The individual was tested in the standing position. The foot of the non-tested leg was placed on a platform 5 cm high, the tested leg hanging freely. The body was fixed by the subject grasping the frame of the chair with both hands and pressing the abdomen and thighs against the supports. The *dynamometer* was adjusted to a level where the horizontal strap embraced the Achilles tendon. A satisfactory fixation of the trunk and thighs proved important for the obtaining of reproducible results (see Fig. 2 e).

Participating muscles: m. biceps femoris, m. semitendineus, m. semimembraneus, m. popliteus, m. gracilis, m. sartorius, m. gastrocnemius, m. plantaris.

EXTENSION OF THE KNEE

Bilateral testing

Dynamometers Nos. V A and B

The individual was investigated in the sitting position with the legs hanging vertically. The straps of the *dynamometers* were placed at the level of the lateral malleolus. To secure a standardized position preventing concomitant extension of the hip, the pelvis was fixed by a strap coupled to the seat of the chair.

Participating muscles: m. quadriceps femoris, m. rectus femoris, m. tensor fasciae latae.

PLANTAR FLEXION OF THE FOOT

Bilateral testing

Dynamometer No. VII. This unit consisted of two metal plates, one for each foot, mounted on a steel axis connected to the strain gauge. The whole *dynamometer* was freely movable in the vertical direction. This arrangement was made to prevent participation of the knee and hip extensors.

The individual was tested in the sitting position. The foot to be measured was fixed to the *dynamometer plate* by a wrist holder whereas the other foot rested on the frame of the chair. Thorough instruction combined with demonstration of the attempted movement proved necessary to obtain reliable results. The force, corresponding to a lever of 30 cm, was recorded, but this value was then converted to a force corresponding to a certain anatomical level. By taking an impression of the foot of the examinee the distance from the axis of the *dynamometer* to the midpoint of the anterior plantar matrix was measured. The force recorded was then converted according to this value (see Fig. 2 g).

Participating muscles: m. gastrocnemius, m. soleus, m. plantaris, m. flexor digitorum longus, m. tibialis posterior, mm. fibularis longus et brevis, m. flexor hallucis longus.

DORSAL FLEXION OF THE FOOT

Bilateral testing

The same *dynamometer* and position were used as for plantar flexion. Instead of the wrist holder, which was found to impede the action of the dorsal flexors, only a leather strap proximal to the metatarsophalangeal joints was used for fixation and transmission of the force. Special attention had to be paid to the exact placing of the foot on the plate to obtain the correct leverage. Correction of the force recorded was made according to the foot size in the same manner as for plantar flexion.

Participating muscles: m. tibialis anterior, m. extensor hallucis longus, m. extensor digitorum longus, m. fibularis tertius.

Evaluation of method

Instrumental equipment

At the construction of the apparatus a complete calibration against known weights was performed. For every strain-gauge unit the whole measuring range was checked. The values obtained showed a linear relation to successively increasing loads. The deviation found was in every case less than $\pm 3\%$. During the whole period of measurement, regular calibration controls were

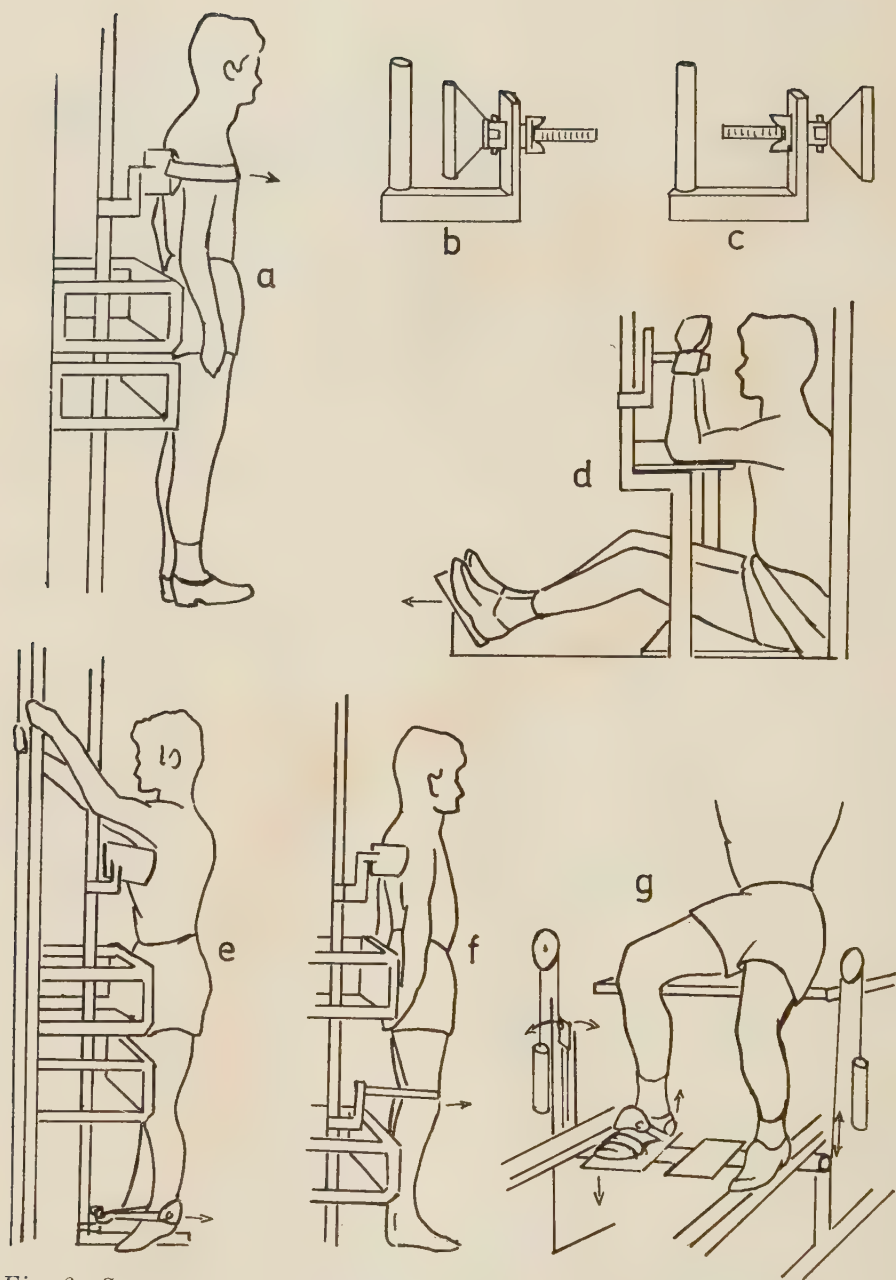


Fig. 2. Some attempted movements; illustration of apparatus and procedure

- a. Position used for forward flexion of the trunk
- b. Dynamometer, adapted for testing of the finger flexors
- c. » » » » » shoulder pull
- d. Position used in leg extension
- e. » » » knee flexion
- f. » » » hip flexion
- g. » » » foot plantar and dorsal flexion

performed at intervals of about 10 days. Here, too, the greatest variations noted were less than 3 %.

Biological factors

A. *Position.* An important question in muscle testing is how variations of angles and external levers influence the force measured. Some theoretical considerations on this problem have earlier been stated by, for instance, Gray (49). Practical studies of the elbow flexors have been performed by Wakim *et al.*, Hunsicker, Clarke *et al.* and Provins & Salter (33, 76, 106, 130). Similar investigations have been made by Elkins *et al.*, Clarke *et al.* and Provins for the elbow extensors, by Elkins *et al.* for the shoulder abductors, by Hettinger for the foot and knee and by Hettinger and Elkins *et al.* for the hip flexors (33, 45, 60). In summary these studies can be said to have shown a great variation in strength of the muscle group when the angle of the corresponding joint was varied. The relationship between angle and force was specific for the special muscle group, although individual variations were found. Alterations of the position of adjacent joints were also shown to influence the strength of a certain muscle group (34, 35, 110). As expected, testing with varying levers established an inverse relationship between force recorded and length of the lever. In the investigations reported there was considerable variation in apparatus as well as testing positions. To verify the validity of their results for the present technique a few experiments were made.

Here three individuals were examined with varying angles and levers of some attempted movements. The following muscle groups were tested: elbow flexion and extension, knee extension, leg extension and forward and backward flexion of the trunk. In principle the results obtained were in close accordance with those of earlier investigators, stressing the importance of standardization as regards positions.

In designing the testing procedure, the following points of view had to be taken into consideration. Positions where small changes of the angles will give large alterations of the force are to be avoided. The muscular tension and internal leverage of the position chosen must not be disadvantageous to the muscles to be measured. The testing positions and fixation arrangements must be relatively easy to bring about and must not be uncomfortable for the subject investigated. The testing procedure chosen represented a compromise between these different aspects.

As regards external leverage the forces were measured at certain anatomical points. It seemed more functional to adopt this approach than to use the same distance from the joint in all persons. If an approximate proportionality

is presumed to exist between internal and external leverages, the forces measured will here be a rough expression of the physiological cross section of the participating muscles.

To study whether the law of leverage was applicable in transformation of forces to torques and vice versa, a series of measurements were performed in the elbow and the knee joint. The product of force and lever was found to be relatively constant at variation of the lever.

B. Sequence of testing. In the present technique a number of muscle groups were examined on the same occasion. Ideally the intervals between the muscle contractions ought here to be long enough for complete recovery.

A testing procedure where these principles were strictly applied would, however, be very time-consuming and tedious. It therefore seemed justifiable to use a testing procedure with constant sequence of testing and with moderately long intervals. To estimate how great are the errors due to fatigue that may be involved in this proceeding, a special investigation was performed. Two groups of 12 and 11 individuals respectively were twice examined with one week's interval. In one group the same procedure was used both times, whereas in the other the sequence was reversed the second time. Statistical analysis did not confirm any effect from the change in sequence. It ought, however, to be mentioned that the material investigated was small.

C. Effect of repeated tests. In repeated muscle testings the individual may possibly attain a higher value after some time because he has become accustomed to the technique. He may thus learn to use the appropriate muscles in a more effective way. This "learning" factor is difficult to isolate, since repeated testing may also give some augmentation of strength owing to the training inevitable with the method.

In studies where one purpose was to study daily variations, the strength was measured three times a week in two individuals for $2\frac{1}{2}$ months (see Fig. 3). The strength curves of different muscle groups varied as regards daily fluctuations as well as changes during the testing period. In some of them, e.g. forward and backward flexion of the trunk, a considerable increase was noted, whereas in others, such as flexion of the knee, there was a moderate decrease. Individual differences were also established. In plantar flexion of the foot one of the subjects showed a successive increase in strength, whereas the other had about constant values. Both individuals were conscripts working in the laboratory as assistants. Except for the physical exertion involved in calibration of the apparatus, none of them had any physical training during the period of investigation.

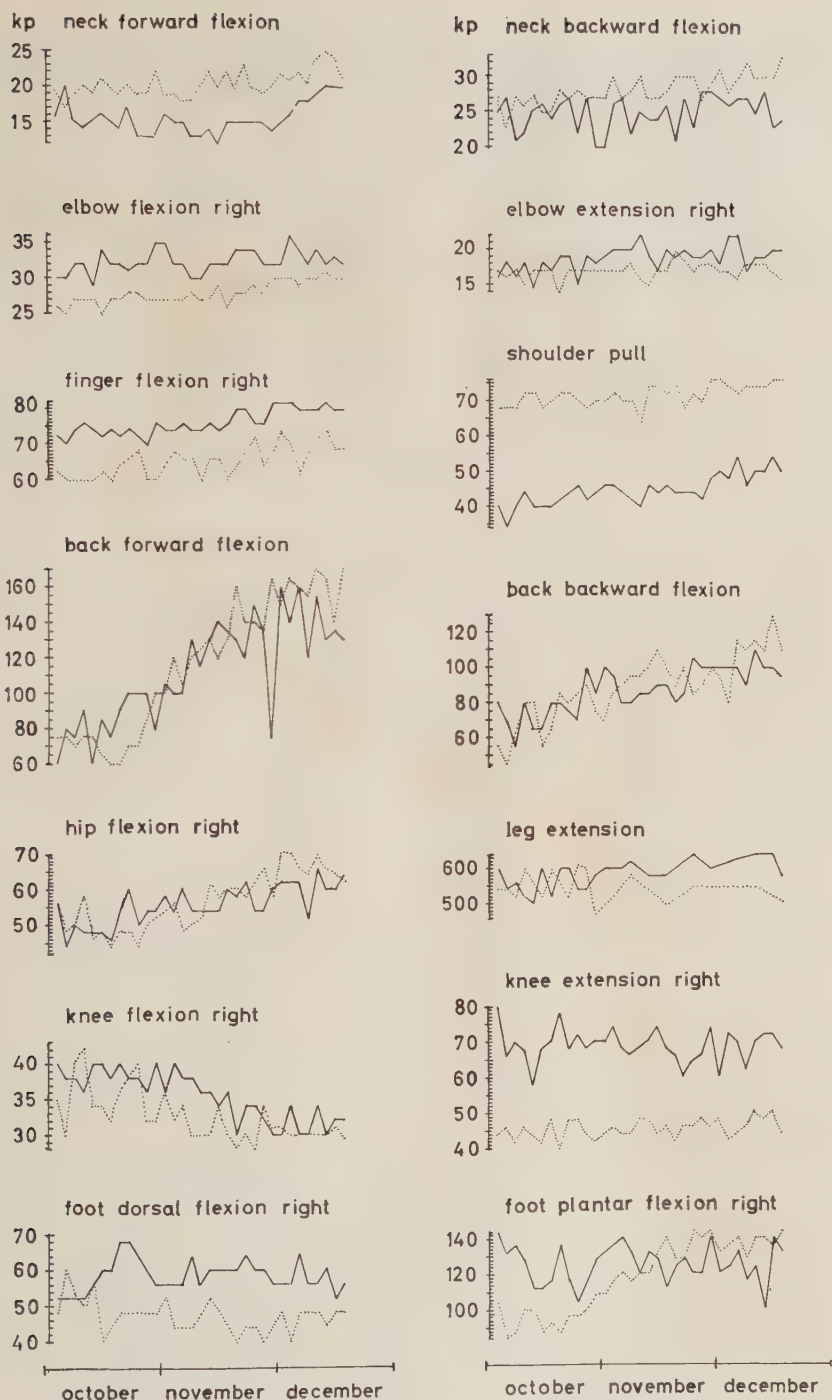


Fig. 3. Repeated muscle-strength recordings in two individuals studied during $2\frac{1}{2}$ months

The subjects investigated were two 20-year-old laboratory assistants in ordinary training condition. All strength values are given in kiloponds.

In evaluation of the alterations mentioned biological changes during the observation time must be taken into account. The increase of values observed may thus partly be due to augmented strength, but at least for some movements, e.g. flexion of the back, an enhanced skill cannot be excluded. It thus seems probable that the "learning" error may be of importance mainly for certain muscle groups, whereas other movements, such as for example elbow flexion and finger flexion, may give a good reproducibility even with frequently repeated testings. In muscles where alterations were observed these first became manifest after 6—7 examinations. It is therefore reasonable to assume that the "learning" error may be reduced if frequent examinations at short intervals are avoided. Further support for this view is obtained from duplicate determinations, in which no significant alterations between two examinations were observed. (See below.)

D. Twenty-four-hours variation. To elucidate the variation of muscular strength during 24 hours three individuals were examined. The tests, including elbow flexion and knee extension, were performed at two-hour intervals in the daytime and once during the night. The testing was continued with two morning examinations on the following day to reproduce the original values. In addition two afternoon values were measured with an interval of some days during the following week. The fluctuations observed were small and did not show any uniform relation to any particular time of the day.

E. Disposition of the individual. Measurement of the muscle strength involves a volitional process, where the attitude of the individual tested will necessarily influence the results. Various kinds of external influences may also modify the power (78). Variations due to the disposition of the individual may, at least to some degree, be reduced in the design of the investigational procedure. To stimulate the cooperation of the subjects—especially the conscripts—it proved to be a good approach to take advantage of their natural competitive instinct. In each case the purpose of the investigation was made clear before the examination. Afterwards the men obtained their own records, giving them the opportunity to compare their own results with those of their fellows. With rare exceptions the interest in the own muscle capacity appeared to promote good cooperation. To obtain as far as possible uniform investigational conditions the author performed all investigations with the aid of an assistant. In this way the testing procedure, including instruction and demonstration, were as far as possible standardized.

F. *Reproducibility.* To establish the reproducibility of the method a series of 44 conscripts was twice investigated with an interval of about $1\frac{1}{2}$ hours between each test. The results showed considerable variations between the different muscle groups. Single movements, as for example elbow flexion, where a satisfactory standardization was possible, showed a good reproducibility. In others, however, where several joints participated and the movements were complex, as for example in flexion of the back, the variability was greater. The variations found for various muscle groups appear in Table 2.

Table 2 Reproducibility at duplicate determinations with about $1\frac{1}{2}$ hours' interval

Attempted movement		$\frac{\bar{x}_1 + \bar{x}_2}{2}$	Diff.	kiloponds		
				s	P	Variation coeff. %
NECK	forward flexion.....	18.0	—0.16	1.90	0.2	7.5
	backward flexion.....	24.7	—0.14	2.01	0.2	5.7
ARM	shoulder pull.....	48.4	—1.54	4.08	*	6.0
	elbow flexion right	30.1	—0.47	1.35	*	3.2
	» » left.....	29.2	—0.32	1.76	0.2	4.3
	elbow extension right..	16.3	—0.44	1.64	0.05	7.1
	» » left.....	15.4	—0.39	1.77	0.2	8.1
	finger flexion right	71.6	—0.36	4.48	0.2	4.4
	» » left.....	66.8	—0.96	4.77	0.1	5.0
TRUNK	forward flexion.....	66.9	—0.93	10.1	0.2	10.7
	backward flexion.....	73.1	+ 1.22	11.8	0.2	11.4
LEG	leg extension.....	396	—1.59	56.0	0.2	10.0
	hip flexion right.....	45.9	+ 0.43	4.63	0.2	7.1
	» » left.....	44.7	+ 0.71	3.34	0.1	5.3
	knee flexion right	29.9	0.0	2.33	0.2	5.5
	» » left.....	29.7	+ 0.48	2.10	0.1	5.0
	knee extension right...	51.3	—0.02	3.16	0.2	4.4
	» » left.....	48.1	+ 1.00	2.67	*	3.9
	foot plantar flex. r....	101.4	—3.76	11.1	*	7.8
	» » » l.....	97.4	—1.13	8.9	0.2	6.5
	foot dorsal flex. r.....	42.7	—0.37	3.79	0.2	6.3
	» » » l.....	41.6	+ 1.46	3.69	*	6.3

Note. Material: 44 conscripts, 19—20 years old, randomly selected from Series A.

Significance of strength recorded with the present method

Maximal voluntary isometric strength is generally accepted as a reliable measure of the ability to perform heavy static or almost static muscular work. As other components of muscular capacity, static and dynamic endurance may be mentioned. Whereas static endurance is rather well correlated with isometric strength (126), the correlation between isometric

strength and dynamic endurance is reported to be lower (32). As pointed out earlier, the method of the author is confined to measuring only isometric maximal volitional strength.

The strength of a muscle is a function of the number and the diametres of the fibres in its physiological cross section, i.e. a section passing through all the fibres. In a muscle with parallel fibres having the same direction as the tendon, the physiological cross section will agree with the anatomical cross section, whereas in for example pinnate muscles this correspondence will be less good (49).

In the majority of movements in the body, several different muscles are usually acting together. The strength of single muscles cannot as a rule be evaluated separately. Under exceptional conditions, as in amputees, where free tendons could be attached to measuring devices, the function of isolated muscles has been studied by Ralston *et al.* (107). Because of the complexity of muscular mechanics in intact man, estimations of the physiological cross section from muscle strength recorded may always involve a series of approximations.

Muscle strength may be recorded either as the force exerted at a certain distance from the moving joint or as the torque developed by the acting muscles.

In principle general laws of mechanics may be applied to muscle physiology. The relation between force and torque is thus defined by the following formula:

$$\text{Torque (kilopond} \times \text{cm)} = \text{force (kilopond)} \times \text{lever (cm)}$$

When denoting the strength of a certain muscle group with the use of the torque no correction is made for the body size of the individual tested. Thus two subjects of different height may have the same torque in a certain muscle group, e.g. the elbow flexors. Because of disparity of levers, their ability to lift weights with the muscle group in question will also be different.

From a practical point of view it will usually be more convenient to measure the force than the torque. This is especially the case with multiarticular movements, where the levers are difficult to evaluate: cf. finger flexion and flexion of the back.

For comparison of the results obtained with different methods, it is essential to know the principle of investigation, the technical equipment, the procedure and the standard position used. If the muscle strength is expressed in different ways, it may be impossible to translate values from one method to another.

The most common way of expressing strength is by measurement of anatomically defined forces (31, 48, 59, 119, 130). In other methods, however, torques are recorded instead (22, 39, 60). The system of muscle testing described by Asmussen *et al.* partly includes modified procedures designed by earlier investigators. Here either forces or torques are used, each for different muscle groups. At presentation of standard values a correction is performed according to individual differences of body height (6). On theoretical grounds it is presumed that the optimal muscle force of an individual might be proportional to the body height in the second power and the muscle torque to the height in the third power. The poor correlation between recorded values and height may be ascribed to the influence of obscuring factors, including the varying training status of the individuals.

In the present study no such transformation of values was performed. For all muscle groups the strength was recorded in terms of external forces, exerted close to the organ used. In this way the ability to perform heavy work with the muscle group could be presumed to be evaluated in a realistic way. Assuming the internal leverage to be proportional to the external leverage, some information may here be obtained regarding the composite physiological cross section of the participating muscles.

Besides the testing procedure, the instrumental equipment is another factor determining the absolute values to be obtained with a given method. In a comparative study by Wakim *et al.* it was shown that strain-gauge instruments will generally give higher readings than mechanical devices such as the cable tensiometer (130). In Sweden perhaps the most commonly used instrument for estimation of grip strength is the Collin dynamometer. It therefore seemed to be of interest to compare measurements obtained by using this instrument with those derived from the strain-gauge equipment of the author.

Before this study was begun, both devices were calibrated against known weights, whereby correct values were obtained at static loading. In Table 3 the means, dispersions and relative dispersions are given for the two methods.

Table 3 Comparison between strength values recorded with two different dynamometers

	Collin dyn. kp				Strain-gauge dyn. kp			
	$\bar{x}$	x	s	$s\%$	$\bar{x}$	x	s	$s\%$
Right handgrip	42.6	0.6	5.2	12.1	67.9	1.3	11.3	16.6
Left * 	40.9	0.6	5.7	14.0	65.1	1.3	11.8	18.1

Series A. N = 79 Conscripts investigated shortly after induction.

Here, too, the strain-gauge method yielded higher absolute values than the mechanical dynamometer. In relative terms, however, satisfactory agreement was obtained with correlation coefficients of 0.60*** and 0.67*** for the right and left handgrip respectively. As pointed out by Wakim *et al.*, the difference between the absolute values may be ascribed to the fact that mechanical devices have a higher internal friction than strain-gauge instruments. The same may be said of the divergent dispersions.

To sum up, it may be concluded that comparisons between absolute values obtained with two different methods are to be avoided. Divergences may be due to the testing procedure and/or the instrumental equipment. If differences in these respects are taken into account comparisons may, however, be performed for evaluation of, for example, relative changes in two experimental series.

Studies on muscle strength

The present method for evaluation of muscle strength was designed with a view to use in clinical as well as social medicine. One of the main aims, however, was to elucidate the possibilities of simple muscle testing in military personnel. The first step in this study was to establish the strength pattern in a series of muscle groups of healthy 19/20-year-old men. As a second question the interrelationship between values from different parts of the body was investigated. The relation to certain anthropometric data was furthermore elucidated. To study how environment may modify muscular strength the values were followed in a group of conscripts during the first year of military service.

Muscular strength pattern in 19/20-year-old conscripts

The method described was tested in a group of conscripts, performing their basic military training (Series A). During the investigation modifications had to be made for several testing phases before the technique could be regarded as definite. Part of the results could, however, be used for elucidation of special questions. For a longitudinal study of the muscular adaptation during the first year of military service a second group was used (Series B). The selection and characteristics of this group are described above. Here the results from the first investigation, shortly after the subjects' transfer from civilian to military life, will be reported.

The above-mentioned muscle strength values were recorded in a group of healthy 19/20-year-old Swedish males, fully fit for military service. As mentioned earlier, the majority of subjects came from the Stockholm area. In civilian life they had mostly light or moderately heavy occupations and 51 % took part in sport, either for exercise or as competitors. From earlier investigations we know that factors such as sex, age, body build and occupation are all of importance in determining the degree of muscular strength (6, 59, 87, 128). Although derived from a randomly selected material, the values reported may be of restricted representativity.

For some of the muscle groups, i.e. handgrip, elbow flexors and knee extensors, a comparison was performed with a corresponding material (Series A), investigated one year earlier. The differences found were small and not

Table 4 Isometric muscle-strength values in 92—93 randomly selected 19/20-year-old military conscripts (Series B)

Muscle group	Kiloponds			
	$\bar{x}$	s	$s_{\bar{x}}$	$s\%$
Neck flexion.....	15.4	3.2	0.3	20.8
Neck extension.....	26.9	5.0	0.5	18.6
Shoulder pull.....	47.7	10.3	1.1	21.6
Elbow flexion right.....	28.3	3.6	0.4	12.7
Elbow flexion left.....	27.7	3.5	0.4	12.6
Elbow extension right.....	16.3	3.0	0.3	18.4
Elbow extension left.....	15.2	2.7	0.3	17.8
Finger flexion right.....	66.5	10.0	1.0	15.0
Finger flexion left.....	62.3	9.7	1.0	15.6
Back forward flexion.....	62.1	15.2	1.6	24.5
Back backward flexion.....	65.4	13.2	1.4	20.2
Leg extension.....	374	94	10	25.1
Hip flexion right.....	45.1	8.7	0.9	19.3
Hip flexion left.....	43.9	8.9	0.9	20.3
Knee flexion right.....	25.1	4.2	0.4	16.7
Knee flexion left.....	24.4	4.1	0.4	16.8
Knee extension right.....	50.0	8.5	0.9	17.0
Knee extension left.....	47.1	8.2	0.9	17.4
Foot plantar flexion right.....	103.2	20.6	2.2	20.0
Foot plantar flexion left.....	97.2	18.2	1.9	18.7
Foot dorsal flexion right.....	39.2	7.2	0.8	18.4
Foot dorsal flexion left.....	38.2	7.4	0.8	19.4

statistically significant. The agreement established may support the view that the values are fairly representative of isometric muscle strength of Swedish national serviceman, at least from this particular recruiting area.

As mentioned earlier, Asmussen *et al.* have described a method using technical equipment similar to that used in the present study. Although testing conditions as well as the material investigated are different, mean values and standard deviations of comparable strength values are roughly of the same magnitude. A detailed comparison is difficult to perform, however, as in the works of Asmussen *et al.* the absolute values of muscle strength are not given, but instead relative values, corrected for the body height of the individual.

The correlation between different muscle groups was studied in the group of conscripts reported above (Series B). The coefficients of correlation between muscle strength values recorded appear in Fig. 4.

As a rule a highly significant correlation was observed between different muscle groups. A good correspondence was especially found between right- and left-sided values as well as between synergists and antagonists.

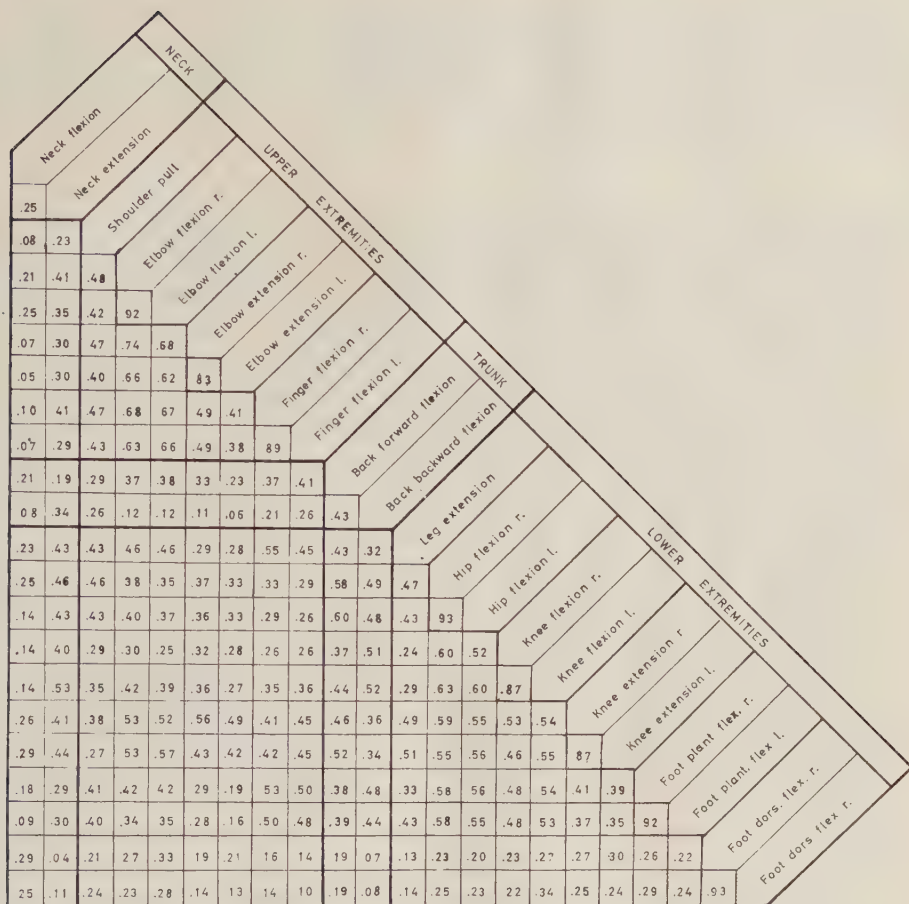


Fig. 4. Correlation between isometric muscle strength recorded in different parts of the body

Series B, $n = 92-93$.

The figures denote correlation coefficients (r). In the present study the correlation was found to be statistically highly significant for $r \leq 0.34$, statistically significant for $r = 0.27-0.34$ and probably significant for $r = 0.21-0.27$.

As expected, muscle groups belonging to the same region appeared to be more closely related to one another than to muscles in other parts of the body. Also within the regions, however, disparities were found, certain movements such as elbow extension, knee flexion and dorsal flexion of the foot showing a somewhat divergent correlation pattern.

The correlation between neck strength and the strength of the upper extremities and the trunk was found to be rather low. This was also the case

for the power of the trunk compared with that of the upper extremities. The correspondence between trunk and leg strength was, on the other hand, stronger. A relatively good agreement was also found between the values of the upper and lower extremities.

Discussion. As pointed out by Lindegård, the muscular distribution of strength in a group of individuals will reflect their habitual motional pattern. A distinction between different muscles according to their use may here be possible (88).

Theoretically each individual is assumed to have a certain range of muscular capacity, which is genotypically determined. The actual phenotypical value may be divided into two fractions, viz. the basic—or minimal—strength and the strength superimposed thereupon by training. The basic strength is supposed to be characteristic for each individual, whereas the second part of the actual value, i.e. the training component, may vary according to the demands of environment.

The basic muscle strength is presumably well correlated in different parts of the body, since it is genotypically determined. The same assumption may be valid for the actual muscle strength, if the individuals are trained according to their physical preconditions in all muscle groups. Selective inactivity or excess training of special groups will, however, disturb this correlation.

These considerations may aid in elucidating the intraindividual variations of correspondence between different muscle groups in the material investigated. As mentioned, some muscles, e.g. neck flexors, elbow extensors, knee flexors and foot dorsal flexors, tended to deviate from the majority of muscle groups in regard to strength. This tendency may at least partly be explained by an aberrant state of training. Other causes, such as variability of the measuring method, must however also be reckoned with.

The conditions mentioned apply to subjects in ordinary physical condition investigated before military service. Different relationships may be expected to exist in material with a different training status. To verify this assumption a number of weight lifters were examined. Here remarkably high strength values were found in, for example, elbow extensors and knee extensors, whereas other muscle groups, as for example hip flexors, seemed to be less trained. Compared with the ordinary conscript material the weight lifters showed different pattern of correlation between the different muscle groups. This may be demonstrated for the muscles mentioned, where a significantly lower correlation was found between hip flexion on the one hand and elbow extension and knee extension in the other, as compared with the conscripts.

		Athletes	Conscripts
Hip flexion	elbow extension	$r = -0.21$	$r = +0.37$
	knee extension	$r = +0.15$	$r = +0.59$

Prediction of general muscle strength from single muscle-group values

The impossibility of determining the total muscularity of an individual will necessarily make all attempts at prediction imperfect. In spite of these limitations there have been devised various methods where different factors are constructed as approximate measures of total muscularity.

Generally a number of muscle groups have been measured and the scores obtained have been combined by simple addition, as in the studies of Clarke, Martin *et al.*, and Bethe *et al.* (18, 32, 95). The procedure mentioned implies that the various muscle values are weighted, each of them being proportionate to the actual strength of movement. The composite value will, however, greatly depend upon the choice of muscle groups as well as on the testing conditions.

Another method, applied by, for instance, Clarke and Lindegård, is based upon the use of standardized scores (32, 88). Here the strength values recorded are converted to standard deviation units after subtraction of the mean values. The average standardized score—total muscle factor—is used as an expression of the entire strength of the body. The formula of this calculation would be:

$$\text{Standardized muscle factor} = \frac{\sum \frac{x - \bar{x}}{s}}{n}$$

- x = a single value of muscle strength
- $\bar{x}$ = the mean strength value of a single group in the material investigated
- s = standard deviation of material
- n = number of muscle groups included in the test

In this technique the muscle groups are given equal weight within the resultant muscle factor. One advantage of this procedure is that exclusion of one or several muscle values will induce only a small error of total muscle factor. Sometimes this cannot be avoided, owing to accidental injuries affecting single joints and muscle groups.

The first technique was used by Martin *et al.*, who constructed a so-called “total proportional strength index” from the values of 22 muscle groups.

The strength was determined by their "breaking method" and in addition the Collin dynamometer technique, the latter being used for testing of the handgrip. The correlation of the single muscle strength values with the resultant index was studied. It was shown that practically all recorded muscle groups correlated well with the total proportional strength according to the definition used. For practical purposes an abbreviated test was designed, in which only a few of the original testing phases were included. It was suggested by the authors that this procedure implied only a slight reduction of accuracy compared to the complete test. In the studies reported, some important muscle groups, such as plantar flexion and hip extension, were not included, because of technical limitations. Similarly the handgrip had to be measured by another method.

In principle the procedures mentioned may not add much further information than would studies of the interrelationship between strength values of different muscle groups. For comparison with the results of earlier investi-

Table 5 Correlation between the strength of single-muscle groups and two expressions for estimated total-muscle strength (Series B n = 92—93)

Muscle group	Summed muscle factor $\bar{x} = 1176$ kp		Standardized muscle factor $\bar{x} = 0.0$ units	
	<i>r</i>	<i>s_e</i>	<i>r</i>	<i>s_e</i>
Neck flexion.....	0.27**	166	0.33**	0.60
Neck extension.....	0.52***	147	0.56***	0.52
Shoulder pull.....	0.57***	141	0.59***	0.51
Elbow flexion right.....	0.64***	133	0.76***	0.41
Elbow flexion left.....	0.64***	133	0.75***	0.42
Elbow extension right.....	0.49***	143	0.67***	0.47
Elbow extension left.....	0.44***	155	0.61***	0.50
Handgrip right.....	0.69***	124	0.68***	0.46
Handgrip left.....	0.64***	133	0.64***	0.48
Back forward flexion.....	0.63***	134	0.61***	0.50
Back backward flexion.....	0.52***	147	0.47***	0.56
Leg extension.....	0.89***	81	0.61***	0.50
Hip flexion right.....	0.72***	120	0.76***	0.41
Hip flexion left.....	0.67***	128	0.72***	0.44
Knee flexion right.....	0.50***	150	0.64***	0.49
Knee flexion left.....	0.58***	141	0.71***	0.45
Knee extension right.....	0.70***	124	0.78***	0.40
Knee extension left.....	0.69***	124	0.74***	0.43
Foot plantar flex. right.....	0.62***	135	0.69***	0.46
Foot plantar flex. left.....	0.59***	140	0.61***	0.50
Foot dorsal flex. right.....	0.28**	165	0.40***	0.58
Foot dorsal flex. left.....	0.29**	167	0.38***	0.59

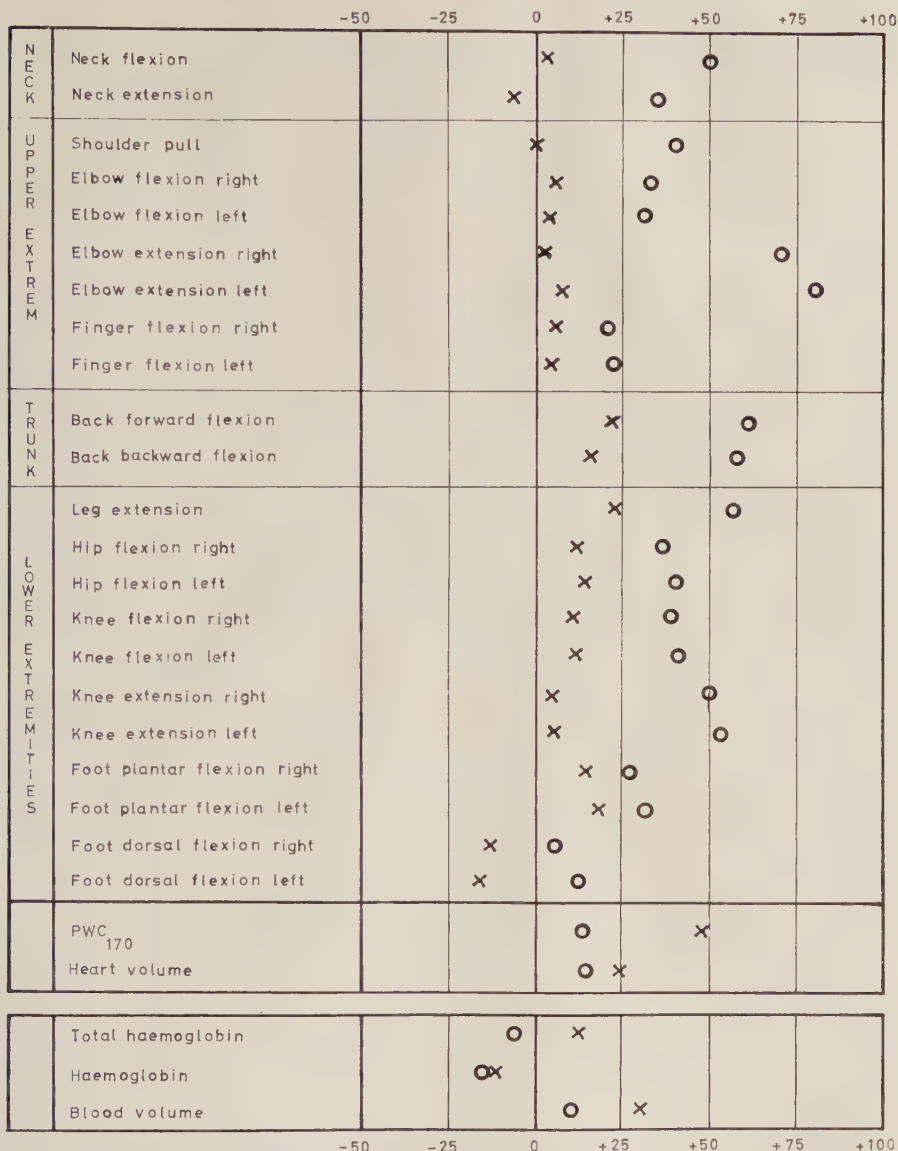


Fig. 5. Isometric muscle strength and some circulatory data, recorded in two categories of elite athletes as compared with individuals in normal training

Symbols: Weight lifters (O) Middle-distance runners (X)

Upper section. Mean values from weight lifters (Series G₁ n = 15) and middle-distance runners (Series G_r n = 23), expressed as percentage deviation of values from a group of randomly selected conscripts (Series B n = 92—93).

Lower section. Mean values from weight lifters (n = 12) and middle-distance runners (n = 22) expressed as percentage deviation of normal standard values of the Clinical Physiological Laboratory of Karolinska Sjukhuset. As the standard in calculation of relative haemoglobin concentration 15.4 g/100 ml was used. For numerical values see Table 6.

gators, however, the use of similar approximate measures of total muscularity in the present study may be regarded as justifiable. From the experimentally obtained strength values two different muscle factors were constructed, one using the raw scores and one consisting of average scores, converted to standard deviation units. The correlation between each of these muscle factors on the one hand and single muscle values on the other is shown in Table 5.

As can be seen, a good correspondence was generally found between single muscle groups and the above-mentioned muscle factors. As pointed out earlier, some muscle groups seemed to be less representative of general muscularity than did other muscles. In contrast to the findings of Martin *et al.*, however, the finger flexors showed about the same correlation with the summed muscle factor as did the majority of muscles.

The muscle factors mentioned may be used as approximate expressions of the general muscularity of individuals. If, however, the ability to perform special forms of heavy work is to be estimated, a closer definition of its physical demands is desirable. For some muscular and circulatory capacity factors this was clearly demonstrated in investigations of two categories of élite athletes. See Fig. 5 and Table 6.

In these studies the effects of selective training were established as muscular and circulatory patterns, specific to the appropriate branch of athletic activity. As regards muscularity, the factors mentioned may only imperfectly reflect the capacity required in highly specialized occupations of this kind. For a better characterization it would be desirable to use some other measure whereby the different muscle values are weighted according to their importance.

For special military occupations the physical demands are not known as a whole. Certain basic physical capabilities, such as a high general muscularity and endurance, may however be assumed to be valuable qualities for élite soldiers. A single-muscle strength value which is shown to reflect general muscle strength may here constitute a valuable piece of information in the selection of individuals for physically hard service.

For practical reasons, muscle groups which are readily accessible for strength determinations and which show a high reproducibility are to be chosen. When these factors as well as representativity for estimated general muscularity are taken into consideration, such test movements as finger flexion, elbow flexion and knee extension may be recommended for abbreviated muscle-strength determinations. The above-reported correlation studies furthermore indicated that the leg strength is more closely related to the strength of the back than is the muscle power of the upper extremities. A combined testing

of both arm and leg-muscle strength will therefore afford a higher accuracy as regards prediction of general strength than will measurements confined to the upper extremity.

Table 6 Muscle strength and some circulatory data in two categories of elite athletes

Determination	Weight lifters				Middle-distance runners				Difference	Probability	
	n	$\bar{x}$	s	$s_{\bar{x}}$	n	$\bar{x}$	s	$s_{\bar{x}}$			
Neck flexion	kp	15	23.1	2.7	0.7	23	15.9	4.4	0.9	7.2	***
» extension	»	15	36.1	4.0	1.0	23	25.4	4.4	0.9	10.7	***
Shoulder pull	»	15	66.8	10.2	2.6	23	47.6	11.6	2.4	19.2	***
Elbow flexion right	»	15	37.7	3.8	1.0	23	30.0	3.1	0.7	7.7	***
» left	»	15	36.5	3.3	0.8	23	28.7	3.5	0.7	7.8	***
Elbow extension right	»	15	27.8	4.1	1.1	23	16.5	2.3	0.5	11.3	***
» left	»	15	27.3	3.6	0.9	23	16.2	2.0	0.4	11.1	***
Finger flexion right	»	15	80.0	9.9	2.6	23	70.3	11.3	2.3	9.7	*
» left	»	15	77.1	8.8	2.3	23	65.0	10.1	2.1	12.1	***
Back forward flexion	»	15	100.5	20.6	5.3	23	76.3	20.3	4.2	24.2	**
» backward flexion	»	15	103.9	20.9	5.4	23	75.7	11.9	2.5	28.2	***
Leg extension	»	15	581	92	24	23	462	93	20	119	***
Hip flexion right	»	15	61.4	8.9	2.3	23	50.3	9.2	1.9	11.1	***
» left	»	15	61.7	9.5	2.5	23	49.9	8.6	1.8	11.8	***
Knee flexion right	»	14	34.8	5.3	1.4	23	27.9	3.5	0.7	6.9	***
» left	»	15	34.0	3.1	0.8	23	27.2	3.5	0.7	6.8	***
Knee extension right	»	14	74.4	10.5	2.8	23	52.6	5.6	1.2	21.8	***
» left	»	15	72.3	10.4	2.7	22	49.9	5.2	1.1	22.4	***
Foot plantar flexion right	»	15	131.2	27.9	7.2	21	119.5	18.8	4.1	11.7	0.2—0.1
» left	»	15	128.7	27.7	7.1	21	115.8	18.6	4.1	12.9	0.2—0.1
Foot dorsal flexion right	»	15	41.6	9.9	2.5	21	34.0	7.4	1.6	7.6	*
» left	»	15	42.8	11.0	2.8	20	32.6	8.1	1.8	10.2	**
PWC ₁₇₀ kpm/min		15	1,177	211	55	23	1,551	151	32	374	***
Heart volume ml		11	869	144	44	22	960	102	22	91	*
Total haemoglobin g		12	790	121	35	22	873	81	17	83	*
Haemoglobin conc. g/100 ml		12	13.27	0.79	0.23	22	13.43	0.60	0.13	0.16	0.5—0.4
Blood volume l		12	5.97	0.88	0.26	22	6.52	0.68	0.15	0.55	0.1—0.05

Relation between muscle strength and certain anthropometric data

In evaluation of muscle strength the purpose of the investigation must be taken into consideration. The best way of expressing strength recorded may vary from situation to situation.

For establishment of the ability to perform heavy, mainly static work, anatomically defined forces will generally be adequate. For follow-up studies in connection with physical training or other environmental influences this way of expressing muscle strength will also be satisfactory. In other situations, however, there may be a desire to evaluate muscle strength with regard to the natural preconditions of the individual.

The assessment of normal values is a general medical problem, and is difficult partly because different definitions may be used for the concept of normality. In some works normal muscle strength has been defined as the optimal—mainly genotypically determined—power of an individual when sex, body build and age are taken into account. In other investigations normal values have been used which are synonymous with the average—phenotypical—strength of individuals having certain biological and social characteristics. From this follows the consideration that genotypical and phenotypical strength will show a good correspondence only in subject groups where each individual is trained according to his physical preconditions.

In the above-mentioned works of Asmussen *et al.* attempts were made to establish optimal values for different categories of individuals by correction of recorded strength with regard to body height. In the present investigation such conversions have not been attempted. Instead it seemed to be of interest to study the actual relation of phenotypical muscle strength to some anthropometric data in the present group of conscripts, homogeneous as regards sex and age.

As a measure of estimated general strength the standardized muscle factor used earlier was applied. In the following table the correlation is set out for some body-build data.

Table 7 Relationship between isometric muscle strength (y) and certain anthropometric data (x)

Parameter	Equation of regression line	r	P
Body height, cm	$y = 0.011 x + 7.98$	0.11	0.3—0.2
Body weight, kg.	$y = 0.047 x + 6.86$	0.56	***
Tibial length, cm.	$y = 0.019 x + 9.24$	0.08	0.5—0.4
Femoral condylar breadth, mm	$y = 0.043 x + 5.83$	0.28	**

Note: Muscle strength is expressed as standardized muscle factor.

Discussion. As can be seen, the correlation between body height and muscle strength was low in the present group of subjects. This was the case with the standardized muscle factor as well as with the strength of single muscle groups. The other measure of skeletal length recorded, i.e. tibial length, also showed a low coefficient of correlation with muscle strength. The skeletal breadth, on the other hand, seemed to be more closely related to muscle strength than was height. Concordant results had earlier been obtained by other investigators from studies on similar subject groups (56, 88). Of the parameters studied the body weight showed the highest correlation with muscle strength. A closer analysis of these conditions is, however, beyond the scope of this investigation.

Muscular and circulatory adaptation in conscripts during military service

During military service people from various occupations and environments are brought together to lead a life in which physical and psychological demands are rather uniform. This situation offers exceptional opportunities to study the process of adaptation to altered environmental conditions. Apart from their theoretical interest, studies of this kind may be of value in the designing of military training programmes.

In Sweden there have been performed comprehensive investigations in which one or several physical capacity factors have been followed in conscripts during the year of basic military training (56, 87, 92). From these studies some general trends of physical adaptation are known. As regards muscle strength, however, our knowledge is still incomplete.

In earlier investigations the strength has been recorded in only a few muscle groups, all belonging to the upper extremities. Many muscles which may be assumed to be of importance for military fitness, such as dorsal musculature, leg extensors and plantar flexors of the foot, have not been included. It therefore seemed to be of great interest to apply the present muscle-testing method to a longitudinal study of the muscular adaptability in conscripts during the nine months of military service (Series B₁).

Plan of investigation. The investigational procedure included clinical examination, heart-volume determination, complete muscle-strength testing, anthropometry and determination of the physical working capacity (PWC₁₇₀), in the order mentioned. The first examination was performed during the first two weeks after induction; the following ones at intervals of three months, the last examination taking place shortly before return to civilian life.

In preliminary studies on conscripts during the preceding year there were gained some experiences which seemed to be of value in designing the present investigation. Thus it was occasionally found that conscripts hesitated to show their real capacity because they feared that high records might result in their being given a harder training programme. In the actual study the subjects were therefore informed that the results would be used exclusively for scientific purposes and that the individual results would not immediately be imparted to the military authorities. The subjects' interest and active cooperation was furthermore stimulated by the arrangement that at the end of the investigation everyone was offered the opportunity to become acquainted with his own values.

All muscle-strength determinations were performed by the author, aided by an assistant. At the time of investigation the method had been in use for about a year, and initial inaccuracies had been corrected. As a rule the examinations were performed between 8 a.m. and 2 p.m.

Results. The mean values from the repeated muscle-strength measurements of different muscle groups are plotted in Fig. 6. For reference the PWC_{170} values, the resting pulse and the heart volume in the prone position are also reported.

As can be seen, the muscle-strength changes in different parts of the body were found to be rather heterogeneous. In some muscle groups the strength showed a tendency to increase during the observation period. This was the case with neck flexion, shoulder pull, elbow flexion, finger flexion and knee flexion. In other muscle groups, however, there was observed an average decline, cf. neck extension, back flexion, hip flexion and knee extension. A third category, viz. elbow extension and leg extension, showed largely unchanged values.

Generally the mean changes were small, only occasionally exceeding 5 per cent of the initial value; sometimes they were not statistically significant. For some groups where a slight gain was recorded—for example shoulder pull and finger flexion—the highest value was observed shortly before Christmas leave, whereas a regression was observed at the last examination before departure.

The physical working capacity (PWC_{170}), which showed a pronounced increase during the first six months, had the same tendency to decline—or stagnate—towards the end of military service. The heart-volume alterations approximately followed those of the PWC_{170} , whereas the resting pulse showed the opposite direction.

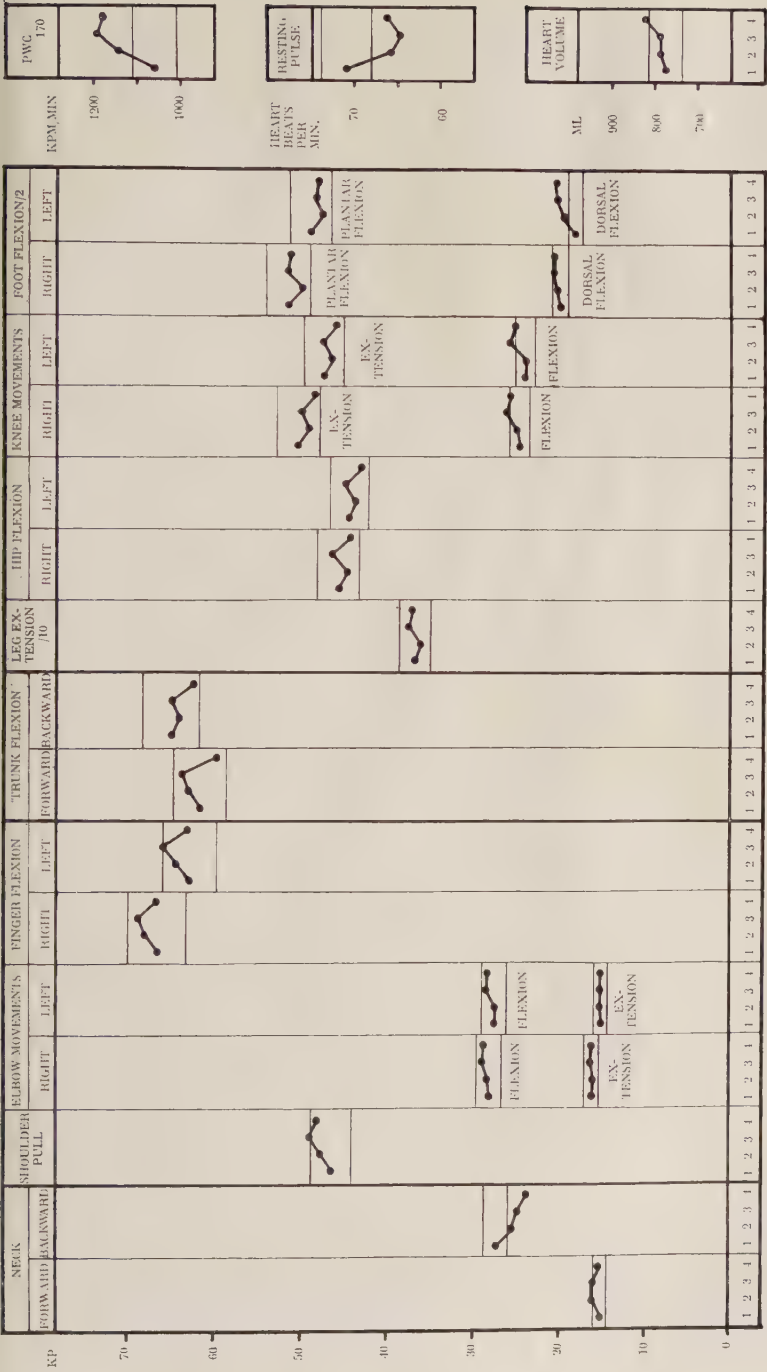


Fig. 6. Average changes of isometric muscle strength and of some circulatory factors in 19/20-year-old conscripts during basic military service

Series B₁, n = 56—58.
 The figures at the foot of the graph denote date of examination: 1 = May 1961, 2 = August 1961, 3 = December 1961, 4 = March 1962. Horizontal lines above and below experimental curves correspond to the range of $\pm 5\%$ of initial value. All muscle-strength values are given in kiloponds. For leg extension, however, the value must be multiplied by 10, and for foot flexions by 2. Numerical values of means, standard deviations and standard errors of the mean as well as significance of differences are set out in Tables 8 and 9.

Table 8 *Muscular adaptation in conscripts during military service* (Series B₁ n = 56 58)

Muscle group	Mean value ($\bar{x}$) in kiloponds				Stand. dev. (s)				Stand. error of the mean ($s_{\bar{x}}$)				Statistic, significance of differences*	
	1	2	3	4	1	2	3	4	1	2	3	4	$P =$ < 0.001	$P =$ 0.001-0.01
Examination No.	1	2	3	4	1	2	3	4	1	2	3	4		
Neck flexion.....	15.2	16.6	16.0	15.8	3.3	4.1	3.8	4.0	0.4	0.5	0.5	0.5	1-2, 2-4	—
Neck extension.....	27.0	25.2	24.4	23.5	4.1	5.1	4.3	4.8	0.5	0.7	0.6	0.6	1-2, 3, 4	—
													2-4	—
Shoulder pull.....	46.6	47.8	49.0	48.1	9.7	9.1	9.7	10.0	1.3	1.2	1.3	1.3	—	—
Elbow flexion right.....	28.2	28.5	29.2	28.9	3.5	3.2	3.6	3.5	0.5	0.4	0.5	0.5	—	—
» left.....	27.7	27.6	28.6	28.4	3.4	3.5	3.6	3.5	0.5	0.5	0.5	0.5	1-3, 2-3	1-4
Elbow extension right....	16.3	16.1	16.4	16.2	2.9	2.8	2.9	3.0	0.4	0.4	0.4	0.4	2-3	1-3, 2-4
» left.....	15.2	15.3	15.4	15.2	2.7	2.7	2.8	2.6	0.4	0.4	0.4	0.3	—	—
Finger flexion right.....	66.6	68.0	68.8	66.7	8.5	7.8	6.9	7.9	1.2	1.1	0.9	1.1	—	3-4
» left.....	62.8	64.4	65.9	63.1	9.3	8.6	8.1	8.2	1.2	1.1	1.1	1.1	1-3, 3-4	—
													1-2, 2-3	—
Back forward flexion.....	61.8	62.8	63.8	59.5	16.5	14.1	13.2	14.6	2.2	1.9	1.7	2.0	—	—
» backward flexion...	65.2	64.2	65.1	62.6	11.4	13.0	11.2	12.3	1.5	1.7	1.5	1.6	—	—
													—	—
Leg extension.....	371	363	376	372	89	84	101	96	12	11	14	13	—	—
Hip flexion right.....	45.6	44.8	46.5	44.3	8.2	8.6	8.3	7.9	1.1	1.1	1.1	1.1	3-4	—
» left.....	44.7	43.9	45.1	43.3	8.9	7.7	8.1	8.8	1.2	1.0	1.1	1.2	—	2-3
Knee flexion right.....	24.9	25.2	26.4	25.9	4.0	3.9	3.8	4.4	0.5	0.5	0.5	0.6	—	—
» left.....	24.3	24.2	26.0	25.3	4.1	3.9	4.4	4.1	0.5	0.5	0.6	0.6	1-3	2-3, 1-4
Knee extension right.....	50.6	49.2	50.1	48.7	8.6	8.1	7.8	8.4	1.1	1.1	1.0	1.1	1-3, 2-3	—
» left.....	47.5	46.7	47.6	46.2	8.2	8.1	8.2	8.0	1.1	1.1	1.1	1.1	—	1-4
Foot plantar flexion right	103.5	100.2	103.6	103.0	20.5	16.5	18.0	18.6	2.7	2.2	2.4	2.5	—	1-2, 4, 3-4
» left.....	98.0	94.9	96.5	97.2	19.2	15.9	16.2	17.2	2.6	2.1	2.2	2.3	—	—
Foot dorsal flexion right	40.1	40.8	41.7	41.7	7.9	7.8	6.3	6.3	1.1	1.1	0.9	0.9	—	—
» left.....	38.6	39.0	40.7	40.7	7.9	8.2	6.3	5.4	1.1	1.1	0.8	0.7	—	—
													1-3	2-3, 1-4

* Figures denote number of examination.

Table 9 Some anthropometric and circulatory factors in conscripts followed during military service (Series B₁ n = 56—58)

Parameter	Mean value ($\bar{x}$)				Stand. dev. (s)				Stand. error of the mean ($\bar{s}_x$)				Statist. significance of differences*			
Examination No.	1	2	3	4	1	2	3	4	1	2	3	4	$P =$ < 0.001	$P =$ 0.001–0.01	$P =$ 0.01–0.1	
Body height, cm ...	178.4	178.5	178.5	178.5	6.4	6.4	6.4	6.4	0.8	0.8	0.8	0.8	—	—	—	
Body weight, kg ...	67.3	68.0	68.1	68.8	7.7	7.4	7.0	7.3	1.0	1.0	0.9	0.9	1–4, 3–4	2–4	1–3	
Femoral condylar breadth, cm ...	9.9	9.9	9.9	9.9	0.39	0.38	0.40	0.39	0.05	0.05	0.05	0.05	—	—	—	
Tibial length, cm ...	40.6	40.6	40.7	40.5	2.2	2.2	2.2	2.2	0.3	0.3	0.3	0.3	—	—	—	
Subcut. fat reg. I.	7.9	7.4	7.3	7.2	2.6	2.0	2.0	2.1	0.34	0.26	0.27	0.28	—	1–2, 1–3, 1–4	—	
II.	6.3	5.6	5.3	5.3	3.6	2.4	2.1	2.1	0.47	0.31	0.28	0.28	—	1–2, 1–3, 1–4	—	
III.	6.8	6.6	6.2	6.0	2.4	2.3	1.9	2.0	0.31	0.30	0.25	0.26	1–4	1–3, 2–4	2–3	
PWC ₁₇₀	1,058	1,138	1,190	1,174	199	180	173	185	26	24	23	24	1–2, 1–3, 1–4	2–3	2–4	
Heart volume, ml ...	770	786	786	819	104	95	93	91	14	13	13	12	1–4, 2–4, 3–4	—	1–2, 1–3	
Pulse resting, beats/min	70.8	65.8	64.7	66.0	11.1	8.6	7.9	9.7	1.5	1.2	1.1	1.3	1–2, 1–3	1–4	—	
Maximal heart rate, beats/min				186.5				8.4				1.1				

* Figures denote number of examination.

Among the anthropometric data recorded, the following may be mentioned. Mean body height was unchanged throughout the nine months of observation, whereas body weight significantly increased, from 67.3 to 68.8 kg. The femoral condylar breadth and the tibial length remained the same. The subcutaneous fat was, however, reduced in all three regions measured, the abdominal fat showing the largest reduction.

A complete survey of absolute mean values, standard deviations, standard errors of mean and significance of differences is given in Tables 8 and 9.

Discussion. At first sight the changes in muscle strength during the nine months of military service may seem somewhat surprising. In particular the occasional decrease in muscle strength in spite of physical training was unexpected. To elucidate the mechanism of these changes a closer analysis of the findings was performed with special regard to the composition of the subject group.

The material was divided into subgroups according to occupation on the one hand and participation in sport activities on the other. Physical working capacity (PWC_{170}) and muscle-strength values of five subgroups appear in Fig. 7.

As regards PWC_{170} the competitive athletes included in the material showed a significantly higher value at the beginning of the observation period than subjects who did not take part in any sport ($P = 0.01-0.001^{**}$). On the other hand the latter group, who started on a lower level, exhibited the greater relative increase of the two. The difference in the changes was, however, not statistically significant.

Comparison between subjects accustomed to heavy work and those previously in light or sedentary occupations showed only a slight, non-significant difference as regards initial values of PWC_{170} . The relative alterations furthermore seemed to be of the same degree for both categories.

Three muscle groups, viz. finger flexors, elbow flexors and knee extensors, were studied in the same respect as PWC_{170} . For these muscles the physically more active subject groups—the competitive athletes and the individuals used to heavy work—showed higher initial values than did the others. The differences were, however, not statistically significant. Although the changes in the subgroups were rather small, they may reflect some tendencies to muscular rearrangement. As a rule the strength curves of initially less capable subjects and of those with higher initial values had a tendency to converge in the course of military service. For knee extension an average decline of strength was observed in the material as a whole. This alteration seemed to be due to a selective decrease in initially strong individuals, whereas weaker

SPORT

OCCUPATION

- competition
- exercise
- x no sport

- heavy or intermediate
- △ easy or sedentary.

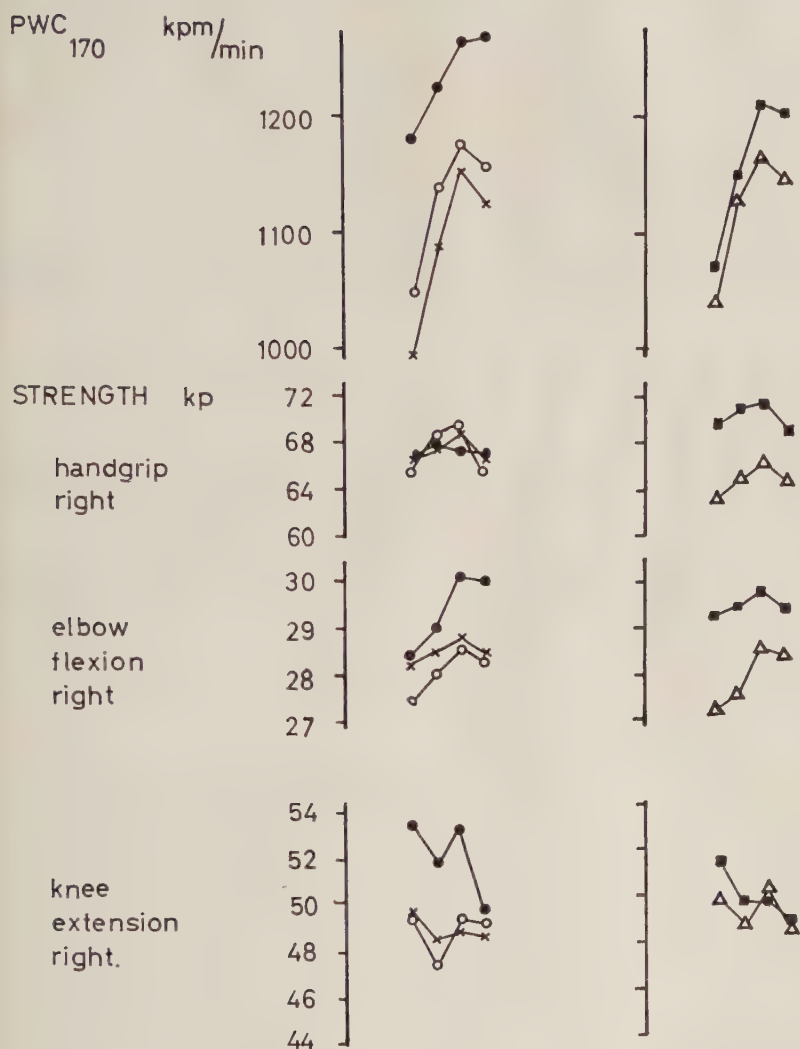


Fig. 7. Changes of isometric muscle strength and PWC₁₇₀ in a group of conscripts, divided into subgroups according to occupation and to participation in sports

Series B₁ n = 58.

Figures at the foot of the graph denote date of examination during basic military service. 1 = May 1961, 2 = August 1961, 3 = December 1961 and 4 = March 1962.

Number of subjects. SPORT: competition 16, exercise 13, no sport 29. OCCUPATION: heavy or intermediate 30, easy or sedentary 28.

individuals largely retained their initial muscle strength. Nor in this case were the differences between the subgroups statistically significant.

Environmental factors such as occupation and participation in sport activities will represent only part of the various civilian influences determining the initial values. This may account for the relatively small differences observed between the different subgroups. Although not conclusive, the tendencies noted may support the view that the initial civilian influences on physical capacity gradually fade during the military service. The results reported are in agreement with those of earlier investigators (56, 87, 92).

As shown earlier, the training level of different muscle groups seems to vary according to their habitual activity. The initial variability, in combination with the varying muscular demands of military life, may explain the heterogeneity of changes found in different parts of the body.

The low degree of changes observed—for most muscles within $\pm 5\%$ of the initial value—would seem to indicate that the general muscular demands of military life are relatively small. On the whole they seem to correspond fairly well to those of average civilian life.

In order to find out whether any particular period of the training time was more effective than others as regards physical improvement, values from the four examinations were compared. As mentioned, a moderate increase of strength was noted in some muscle groups. Here the maximal values were generally reached after about six months, whereas a slight decline was observed towards the end of the training period. A similar tendency was found for the physical working capacity and—although in the opposite direction—for the resting pulse.

In the present material the average physical working capacity (PWC_{170}) showed a statistically significant increase between induction to military service and departure therefrom. A corresponding development was found in 1958—59 by Hellström, who followed a group of conscripts with a similar civilian background. Other conscript groups investigated by Linroth in 1952—53 showed a moderate average decrease of PWC_{170} between two examinations during basic military training. As compared with the present finding this may partly be explained by divergent composition of the material studied, as regards age, civil occupation, residence, participation in sport, etc. Partly however, it may be due to the fact that the first examination of Linroth was performed 1—2 months after the beginning of military training. The initially recorded values in his series were also considerably higher than those observed in the present material.

The mean body weight showed a small but statistically significant increase, whereas the body height was constant throughout the investigation.

Unchanged, also, were the length of tibia and the distance between the femoral condyles on the right-hand side. The amount of subcutaneous fat, estimated in three regions, exhibited a statistically significant decrease.

The stationary body height would seem to indicate that skeletal growth had largely ceased in the present material before induction into military service. This finding is in close agreement with the results of Linroth's investigations, where the mean age was 21 years. In Hellström's series, however, a significant increase of body height was recorded during the first three months of military service. As this change was observed exclusively during the first phase of the period, a small age difference in the two subject groups may account for the disparity. Moreover the initial body height of Hellström's group was somewhat lower, possibly indicating an overrepresentation of individuals whose growth was not entirely completed at the time of induction.

The gain of weight followed the increase of physical working capacity, whereas the amount of subcutaneous fat showed a contemporaneous reduction. The decrease of fatty tissue may probably be attributed to the effects of physical training. The gain of weight, on the other hand, may have different causes. It may here be recalled that the increase was relatively small—amounting to 2.2 per cent of the initial weight. This alteration may partly be explained by changes of heart size and blood volume connected with circulatory adjustment to physical training. Other factors, such as for example developmental or seasonal changes of body composition, are however also to be reckoned with.

PART III

Studies on maximal physical working capacity

The aim of this part of the investigation was to elucidate some problems connected with the evaluation of maximal working capacity. A method earlier described by Grosse-Lordemann & Müller was here applied to investigations of military and civilian subject groups (50).

The average relationship was thus established between work intensity and maximal performance time. The reproducibility of an index of maximal physical working capacity was tested in duplicate determinations on separate days. Exhausting work of varying duration was furthermore studied with regard to circulatory adaptation. The results obtained in subject groups of divergent composition were compared, and differences in final heart rate and lactic-acid concentration discussed. Finally the present technique was compared with some other methods for assessment of physical capability.

CHAPTER VI

Earlier investigations

Numerous techniques have been devised for evaluation of physical working capacity. The type of test work, as well as the technical details, varies from method to method. Certain requirements are, however, essential to obtain reproducible results. The work must be fairly simple and familiar to the individuals tested. Furthermore, it must be possible to grade the work intensity objectively. These requirements are largely fulfilled by the work on a bicycle ergometer (61, 71).

The testing method may be either maximal or submaximal. In submaximal tests the work load is generally related to the heart rate (43, 103, 117, 129). These methods have the advantage of objectivity, and they may be applied also to the examination of diseased persons.

Where it is possible to use maximal performance tests, they will offer a more realistic way of estimating the physical working capacity. In one of the maximal testing methods the greatest attainable oxygen uptake—the so-called aerobic capacity—is used as an expression of physical working capacity (11, 58, 63, 118, 125). Although this measure may afford a reliable value of endurance, the method is hard to apply in large subject groups because of its great technical and personnel requirements.

Other approaches have been used, where the work load is related to the maximal performance time or to that time combined with other factors. Among methods using this principle the following may be mentioned.

Johnsson & Brouha tested a group of men running on a motor-driven treadmill at 7.0 miles per hour on a gradient of 8 %. The subjects had to run until exhaustion or for a maximum of 5 minutes. From maximal pulse, maximal serum lactate concentration and duration of run, a work index was calculated (79, 80). Foltz *et al.* used a test of exhaustion, where double work periods were applied in order to reduce the individual variations (46). Taylor described another method, where the work on a treadmill was gradually increased until the subject became exhausted. The maximal time was here used as a so-called performance index (124).

Grosse-Lordemann & Müller studied the relation between work load and maximal time during which the load could be sustained. They used an electrodynamically braked bicycle ergometer of their own design. In their experimental series maximal tests with varying loads were performed with 5 individuals (50, 99—102, 104). The probable formula reflecting the relationship between work intensity and maximal performance time was established. The influence of different variables, such as pedalling velocity, height of saddle and length of pedals, was determined. Investigations of the mechanical efficiency were furthermore performed for exhausting work of varying duration. In accordance with the formula of the load-time curve a value of maximal working capacity could be calculated for each subject investigated. Similar investigations were carried out by Bink, who studied the relationship between effort and endurance in 5 individuals (20).

From the world records for running various distances the relation between mean velocity and performance time was studied by Hill, Henry, Lietzke and Apéria *et al.* (1, 57, 63, 86). The data were plotted in a coordinate system and the resultant curve analysed. A curve similar to that of Grosse-Lordemann & Müller was obtained. On the basis of these findings a technique for evaluation of maximal working capacity was suggested, using as a measure of physical fitness the work intensity sustainable during a maximum of 6 minutes.

In connection with studies on physical performance and perceived exertion, a test for short-period work on the bicycle ergometer was recently described by Borg (23). Maximal work was here recorded in performances lasting for about 45 seconds, using a gradually increasing work load. It was suggested that the level attained reflected mainly muscular capacity and motivation.

Methods

A. Submaximal evaluation of physical working capacity (PWC_{170})

As a matter of routine practically all the subjects admitted to the laboratory were investigated according to the method developed at Karolinska Sjukhuset (117, 129). The working capacity is expressed as the work intensity which the individual can maintain at a heart rate of 170 beats per minute in circulatory steady state. The latter concept was defined as the condition where the pulse rate increased 10 beats or less between the 2nd and 6th minutes at the highest load. When the subject did not fulfil this criterion, the working capacity was instead related to a pulse level of 160 beats per minute.

The working machine used was an electrodynamically braked bicycle ergometer (71). The five ergometers in use were regularly calibrated twice annually. In no instance did the variation exceed 3 per cent. For the electrocardiographic recordings a direct-recording apparatus was used (Mingograph 42, Elema-Järnh, Stockholm).

Procedure. Prior to the work test an Ecg at rest, as well as an orthostatic test, was performed. The following leads were used: standard leads I, II and III and precordial leads CR_1 or CH_1 , CR_2 or CH_2 , CR_4 or CH_4 , CR_5 or CH_5 and CR_7 or CH_7 . (The head leads were taken during work.) For the orthostatic test, the heart rate and Ecg reaction were studied after 8 minutes of passive standing. The work test was initiated at a load of 300 kpm/min. Every 6 minutes the load was increased, until the pulse rate reached a level of 170 beats per minute. To study the effects of maximal work the test was in some subject groups continued until exhaustion. Pulse values were followed at Ecg every two minutes. An Ecg was also recorded immediately after the work period and following 4 minutes of rest. Using the approximately linear relationship between pulse rate and work load the value of PWC_{170} was obtained by extrapolation or intrapolation.

B. Maximal oxygen uptake ($\dot{V}O_{2\max}$)

In each individual the measurement was preceded by repeated work tests, where the maximal performance times were determined for different loads.

In connection with these experiments the subjects were trained to breathe into an air-collecting system. At determination of maximal oxygen uptake the examinees were tested on two or more loads of different severity. The load was kept constant during each work period, and the subject had to work until exhaustion.

Timed air collections were carried out through a rubber mouthpiece, low resistance valve and a short length of tubing leading to a Douglas bag. Before collection the tubing system was flushed with exhaled air for $\frac{1}{2}$ —1 minute.

Sampling was performed repeatedly during each work period, and immediately before the end of work two bags were taken in rapid succession. From each bag two samples were drawn for duplicate determinations. During experiments with a high work load the collection periods varied between 30 and 45 seconds. For easier loads the exhaled air was collected during 30—70 seconds.

The gas volume was measured at constant suction through a dry gasometer (Nordgas) and collected into recipients. The analysis for oxygen and carbon dioxide was performed with the Haldane apparatus. From the volume and composition of inhaled and exhaled air the rate of oxygen consumption was obtained for each period correcting for volume change which is apparent from different nitrogen concentrations.

C. Evaluation of maximal physical working capacity (PWC_{max})

For studies of maximal working capacity the above-mentioned technique suggested by Grosse-Lordemann & Müller was utilized. Some modifications and additions were, however, introduced.

The work was performed on an electrically braked bicycle ergometer, using a pedal rate of 60 revolutions per minute (71). The effect here remains approximately constant even if the pedalling rate is varied between 50 and 70 r.p.m.

In contrast to the submaximal method described, where the load was increased stepwise during the work period, the examinee was here tested on constant loads. The examination included several such performances on separate days and with varying loads. Each time the work was continued until exhaustion. The time of maximal performance was recorded with the aid of a stop-watch. The number of work periods was determined by the aim of the special part of the investigation.

The values obtained were plotted in a coordinate system with the work

load on the abscissa and the maximal performance time on the ordinate. The resultant curve was shown to have a characteristic shape in agreement with the findings of earlier investigators. By intra- or extrapolation, according to the standard form of the curve, the relation between work load and maximal performance time could be estimated for different time values. As a measure of one type of physical working capacity, the work load which could be sustained for a maximum of 6 minutes was chosen. Figures representing other kinds of physical working capacity can, however, be obtained, if other points of the experimental curve are used.

Dependence of maximal performance time on work intensity

For elucidation of the relation between work intensity and maximal performance time a group of 28 civilian volunteers was investigated (Series F). Each subject here had to participate in 2—5 or occasionally more maximal work tests on separate days. The whole series of performances extended over a period of 2—4 weeks. The intervals amounted to 1—14 days.

The repeated work periods necessary for the study may be suspected to involve some degree of training. To minimize the effects of accidental physical improvement, the sequence of work intensities was varied irregularly from individual to individual. The number of performances included in the calculations was furthermore limited to five.

Results. The shape of the curves obtained indicated a linear relationship between logarithmic values of work load and maximal performance time according to the formula suggested by Grosse-Lordemann & Müller (50).

$$\log T = p \cdot \log N + q + z$$

T = time of maximal performance in minutes

N = work load in kilopondmetres per minute

p and q = constants z = disturbing factors

The regression equation was computed for each individual. A high correlation was established between the logarithms of work load and maximal performance time ($r = 0.88-0.99$, $P < 0.001^{***}$). The results seemed to verify that the above-mentioned formula will afford a satisfactory approximation within the time limits studied, viz. between about 1 and 18 minutes. Single values corresponded to a maximal performance time of under 1 minute or more than 18 minutes. In these ranges the experimental data were too scanty to permit definite conclusions regarding the relationship mentioned.

In Table 10 are given the individual results, including values for the constants p and q as well as angle of inclination and estimated physical working capacity during 6 minutes ($\text{PWC}_{\text{max } 6'}$).

Table 10 Data obtained from maximal performances in 28 civilian volunteers

Subject	Number of work periods	constant <i>p</i>	constant <i>q</i>	angle alpha	PWC _{max 6'} kpm/min
1	4	— 3.95	+ 13.42	75.8	1,580
2	3	— 4.03	+ 13.16	76.1	1,180
3	5	— 3.85	+ 12.89	75.5	1,420
4	5	— 5.64	+ 18.65	79.9	1,480
5	5	— 4.96	+ 16.64	78.6	1,590
6	4	— 3.31	+ 11.50	73.2	1,690
7	4	— 4.43	+ 15.11	77.3	1,700
8	5	— 4.22	+ 14.00	76.7	1,360
9	2	— 4.57	+ 15.56	77.7	1,730
10	3	— 4.70	+ 15.77	78.0	1,520
11	2	— 4.08	+ 14.02	76.2	1,760
12	3	— 6.39	+ 21.24	81.1	1,590
13	3	— 4.37	+ 14.32	77.1	1,260
14	2	— 11.63	+ 38.05	85.1	1,610
15	2	— 4.72	+ 16.14	78.0	1,770
16	3	— 5.56	+ 18.82	79.8	1,770
17	3	— 6.25	+ 19.69	80.9	1,060
18	2	— 5.00	+ 15.81	78.7	1,010
19	5	— 4.24	+ 14.13	76.7	1,390
20	4	— 5.72	+ 18.96	80.1	1,510
21	5	— 4.58	+ 15.42	77.7	1,570
22	3	— 8.73	+ 29.04	83.5	1,730
23	5	— 4.40	+ 14.99	77.2	1,700
24	5	— 5.35	+ 17.88	79.4	1,570
25	4	— 5.19	+ 17.00	79.1	1,340
26	4	— 4.77	+ 16.25	78.2	1,780
27	4	— 3.55	+ 11.70	74.3	1,190
28	5	— 4.62	+ 15.44	77.8	1,490

The present results were furthermore compared with the findings of Grosse-Lordemann & Müller. In Fig. 8 the curves from their five examinees are approximately reproduced, together with those of the present study.

As shown above, the inclination of experimental double-logarithmic curves reveals variations from individual to individual. The inclination was defined by the smallest angle between the regression line and the abscissa (alpha). For each subject this angle was calculated from the tangent of the angle. For the entire group the mean value as well as the standard deviation of the angle were computed.

Besides the above-mentioned group of civilian volunteers a series of 52 ordinary conscripts (Series D) was investigated in a similar way. In this investigation each individual had to work on two different work loads during the same day with an interval of about 4 hours. On a following day the procedure was reversed. Only data from the first work period of the day were used for the present study. The inclination was here computed only from two experimental points.

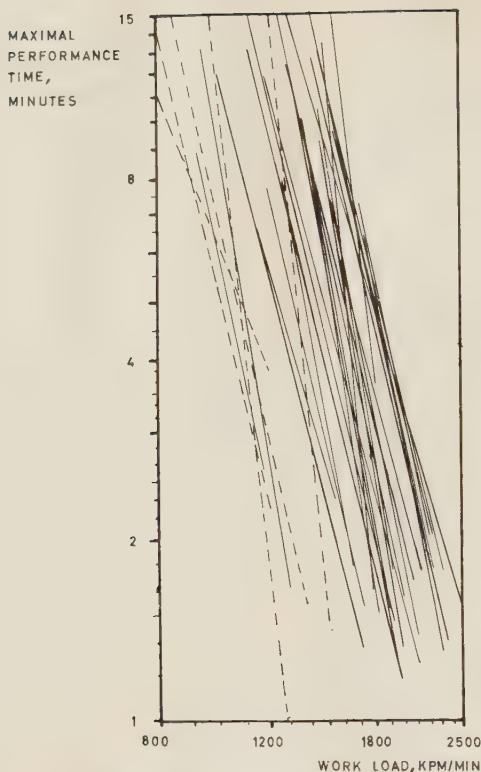


Fig. 8. Double logarithmic graph illustrating the relation between work load and maximal performance time

The broken lines represent results from investigations on five subjects, reported by Grosse-Lordemann & Müller (1900). The continuous lines give the regressions computed from maximal work tests in a group of civilian volunteers (Series F, $n = 28$).

In Series F the mean angle was $\bar{x} = 78^{\circ}.2 \pm 0^{\circ}.5$, $s = 2^{\circ}.5$, and in Series D it was $\bar{x} = 78^{\circ}.6 \pm 1^{\circ}.1$, $s = 8^{\circ}.0$. The difference was not statistically significant ($P = 0.8-0.7$).

Discussion. The relation between work intensity and maximal performance time was shown to imply that the performance time increases in a predictable way as the work load is put lower. In the present study the formula suggested by Grosse-Lordemann & Müller was confirmed in a larger group of subjects. The experiments were, however, confined to exhausting work with a duration of between about 1 and 18 minutes.

The maximal physical working capacity may be defined as the maximal work intensity for a certain type of work which can be sustained during a certain period of time. The relationship found between work intensity and maximal performance time indicates that small changes in the maximal physical working capacity will correspond to comparatively large changes in the maximal performance time provided the work intensity is kept constant.

As mentioned, the inclination of the double logarithmic curve varied from subject to subject. The interindividual variation was considerably larger in the conscript group D than in the civilian group F. This can at least partly be explained by the inaccuracies involved in calculation of the angle from only two experimental points. The small and statistically insignificant difference of inclination between two series furthermore indicated that the interindividual variability may on the whole be relatively moderate.

From their investigations Grosse-Lordemann & Müller suggested that the variation of inclination of the load-time curve may be due to disparities in the relation between aerobic and anaerobic capacities. In what follows the importance of these two types of energy supply will be elucidated.

As compared with the results of earlier investigators, the values of the present group were generally on a higher level. The inclination of curves, however, seemed to vary within about the same limits. When comparing the characteristics of the two subject groups, it was found that the German subjects were considerably shorter and lighter than the Swedish ones. The material of Grosse-Lordemann & Müller consisted mainly of laboratory personnel of both sexes, whereas the Swedish group included only males, usually above average in regard to physical working capacity. This may account for the differences observed.

Reproducibility of estimated maximal working capacity ($PWC_{\max 6'}$)

The reproducibility was investigated in a group of conscripts undergoing aptitude tests for submarine service (Series E). Each subject had to participate in duplicate maximal work tests on separate days. The work load, which was the same on both occasions, was chosen to give a maximal performance time of about 6 minutes.

For each experimental value the $PWC_{\max 6'}$ was estimated according to the following formula:

$$\log X = \frac{\log T - \log 6}{\text{tg } \alpha} + \log N$$

X = estimated work load, corresponding to maximal performance time of 6 minutes ($PWC_{\max 6'}$).

N = work load used

T = maximal performance time

α = angle between the double-logarithmic line and the abscissa

In the above-mentioned procedure the $PWC_{\max 6'}$ -value was estimated from one experimental point according to the empirically established average relationship between work load and maximal performance time. The values were thereby made comparable.

This transformation will involve some degree of approximation, owing to individual variations of the line. In Fig. 9 some information is given regarding the magnitude of this error. Here values representing $PWC_{\max 6'}$ were calculated for Series F using two different procedures. One figure was computed from the regression equation of 2—5 load-time values, whereas the other was estimated from only one point according to the mean inclination of the double logarithmic line. The latter, more approximate value was, expressed as a percentage of the first, put in relation to the maximal performance time.

The variability was computed for performances of varying duration, i.e. between 1 and 2 minutes, between 2 and 12 minutes and between 12 and about 25 minutes. The variability amounted to 4.5, 2.7 and 4.0 %, respectively.

As shown, the extrapolation procedure with an average regression line will involve only a moderate discrepancy as compared with the more exact method with individual regression lines, provided the experimentally derived maximal performance time falls within the time limits studied. In the use of estimated values of $PWC_{\max 6'}$ for calculation of reproducibility the error of divergent individual inclination will thus be relatively small.

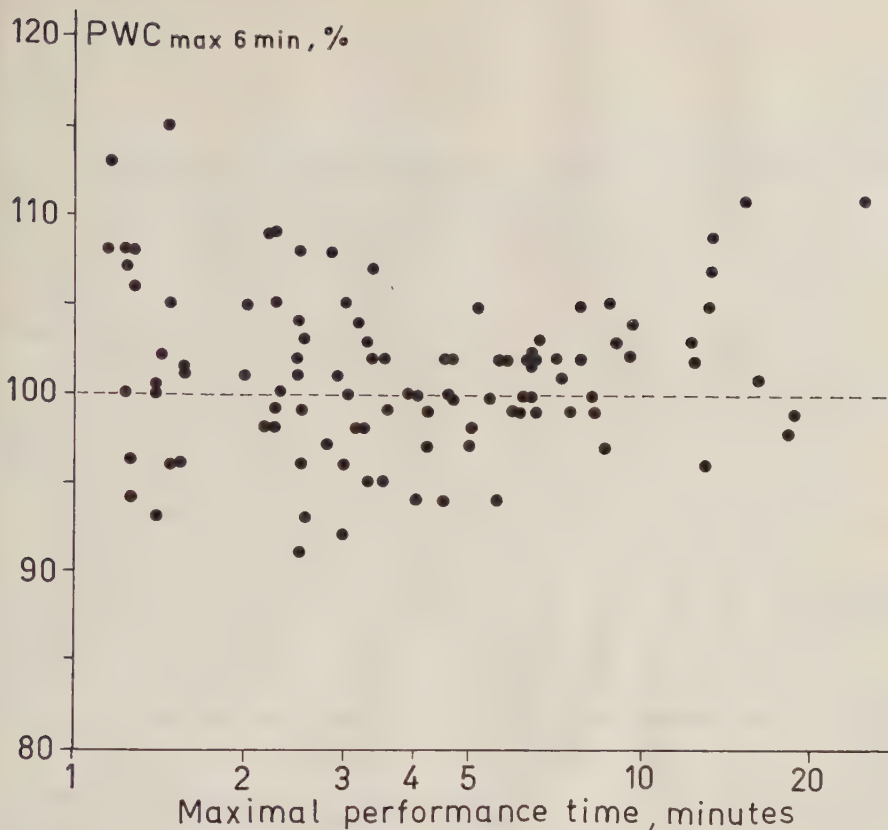


Fig. 9. Error induced by calculation of $PWC_{\max 6'}$ from one maximal performance as compared with the value derived from repeated work periods

In each subject the work intensity sustainable during 6 minutes ($PWC_{\max 6'}$) was calculated with the aid of the individual regression line of 2—5 load-time values. For each of the performances the $PWC_{\max 6'}$ was furthermore estimated according to the average relationship between work load and maximal performance time. In the graph the latter values are expressed as a percentage of the more exact figures derived from repeated work periods.

For the capacity of exhausting work during a maximum of 6 minutes ($PWC_{\max 6'}$) as estimated from duplicate performances, the variability was found to be 4.1 % of the mean value. The figures of the second work period were on average slightly, although not significantly, higher than those of the first performance ($n = 36$ $\bar{x}_1 = 1,465$, $\bar{x}_2 = 1,483$; *diff.* 18 kpm/min. $P = 0.3-0.2$).

The experimental values of work load and corresponding maximal performance time are plotted in Fig. 10, in the form of a nomogram. It is possible to read estimated $PWC_{\max 6'}$ directly from each experimental point. The average inclination found in Series D is here used for the transformation.

WORK
LOAD
KPM/
MIN

ESTIMATED
VALUE OF
PWC_{max 6'}

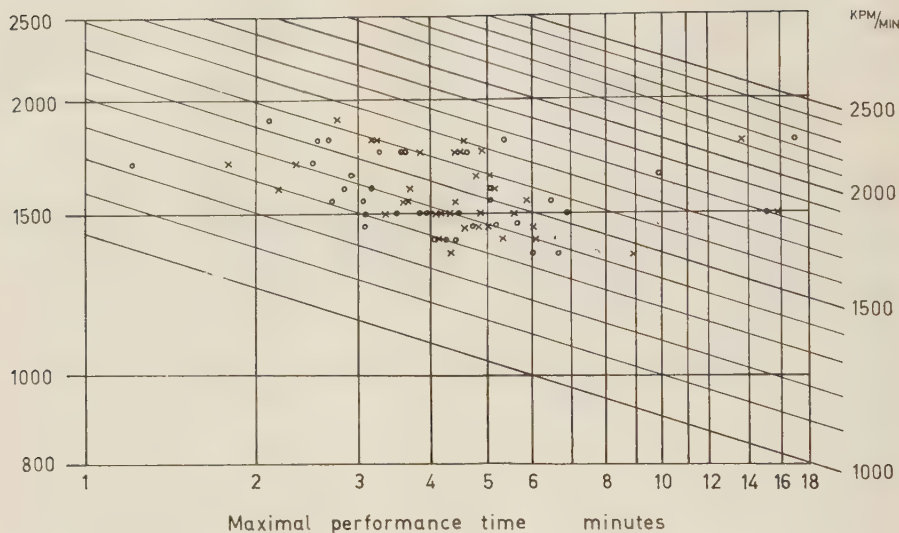


Fig. 10. Work loads and maximal performance times from reproducibility studies on exhausting work

Series E, $n = 36$

Experimental values of work load and maximal performance time are given in a double logarithmic graph. The oblique lines of the nomogram illustrate the average relation between work load and maximal performance time, established in Series D. The estimated $PWC_{max 6'}$ may here be read directly from each experimental point.

Symbols: 1st performance o, 2nd performance x.

Circulatory adaptation in exhausting work of varying duration

Final heart rate after maximal performances of varying duration

The pulse reaction was studied in a series of experiments in which each individual had to work on different loads until complete exhaustion. Two different subject groups were investigated, viz. a group of civilian volunteers and a group of ordinary military conscripts.

The heart rate was recorded by Ecg, the final rate being measured during 10 heart cycles immediately after termination of work.

Comparisons between heart rates calculated before and after the end of performances had shown only minor differences. The post-exercise values were thus on average somewhat lower than the pre-termination rates ($n = 96$, $\bar{x}_1 = 179.5$, $\bar{x}_2 = 177.0$; $\text{diff.} = 2.5 \text{ beats/min} = 1.4 \% \text{ of the first value}$). For shorter performances as compared with longer ones this difference was of about the same magnitude (duration range 45"—5'59"; $\text{diff.} = 2.8 \text{ beats/min}$, duration range 6'—18'; $\text{diff.} = 2.1 \text{ beats/min}$). The use of either value will therefore be equivalent for the purpose of the present investigation.

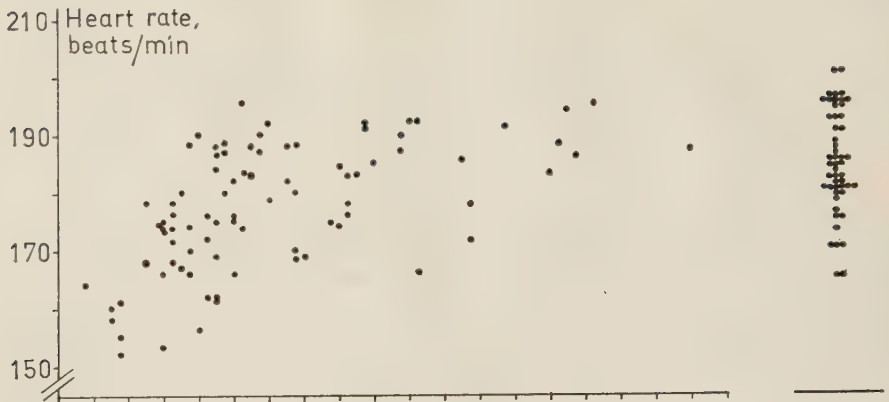
In the group of civilian volunteers (Series F) each subject participated in a series of exhausting performances with different loads. For 28 individuals final pulse rates were recorded in a total of 125 work periods.

In the group of conscripts (Series D) each man had to work on two different loads during the same day with an interval of about 4 hours. On a following day the procedure was reversed. For the present study only the results from the first work period of each day were used. Data were collected from 43 individuals. The work intensities chosen corresponded to maximal performance times of between about 1 and 18 minutes.

In Fig. 11 the heart rates recorded immediately after termination of work are put in relation to the maximal performance times. By relating the pulse values to maximal work times instead of work loads the data were better adjusted to individual capabilities. For comparison the pulse rates were also recorded after maximal work with graded loads. (See page 61.)

As can be seen, the heart rates recorded immediately after exhausting work showed characteristic differences corresponding to the duration of the work.

Series D



Series F

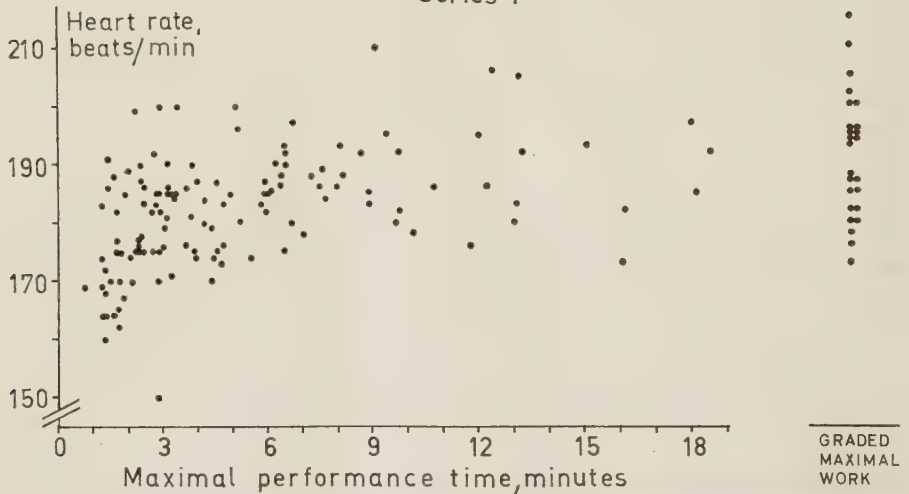


Fig. 11. Final heart rates after exhausting work of varying duration in a group of 19/20-year-old conscripts (D) and in a group of civilian volunteers (F)

The work loads were chosen to give maximal performances with a duration of between 1 and 18 minutes. On the right are given the final heart rates for exhausting work with work loads increased stepwise.

For Series D, where each individual was represented by two such performances, means were computed for groups of experimental points corresponding to average maximal performance times of 3.0 and 6.1 minutes respectively. The difference between the mean final heart rates was here statistically highly significant ($n_1 = 27$, $\bar{x}_1 = 170.3$, $n_2 = 25$, $\bar{x}_2 = 181.1$;

diff. = 10.8 beats/min, $P < 0.001^{***}$). The final pulse value corresponding to a mean duration of 6.1 minutes was furthermore compared with the pulse level attained after graded exhausting work. The latter lasted on average for about 26 minutes. This difference was, however, not statistically significant ($n_2 = 25$, $\bar{x}_2 = 181.1$, $n_3 = 51$, $\bar{x}_3 = 184.3$; *diff.* = 3.2 beats/min, $P = 0.2-0.1$).

In Series F the examinees, as mentioned, took part in several exhausting performances. For each individual as well as for the entire material the experimental points could be connected to a curve of characteristic shape. The level of this curve was found to vary between individuals as well as between subject groups. (See Fig. 16.) The group of civilian volunteers was divided into three partly overlapping subgroups (g—i). It was here possible to calculate intraindividual differences of maximal heart rates attained after strenuous work of varying duration. The results of this study appear in Table 11.

Table 11 Final heart rates in Series F divided into subgroups

Subgroup	n	Maximal performance time			Mean heart rate beats per minute	Diff. b/min	P
		Range Min.	Mean value Min.	time sec.			
g	18	0—3	1	57	176	+ 8	<0.001***
		3—6	4	23	184		
h	21	3—6	4	17	184	+ 4	0.001— 0.01**
		6—18	10	20	188		
i	25	6—18	10	00	189	+ 2	0.3—0.2
		19—34†	27	25	191		

† Graded maximal work.

As shown above, final heart rates were significantly lower after exhausting performances of short duration—2 to 4 minutes—than after longer work periods. On the other hand, no significant difference was established for maximal pulse values after strenuous work lasting about 10 minutes and those after the more lengthy work in the graded work test.

In order to eliminate interindividual variability the data of Series F were also expressed in relative terms. For each individual the heart rate attained after the graded maximal test was denoted as 100 per cent. The rates recorded after the shorter work periods were expressed as a percentage of the value mentioned. The results of these calculations are shown in Fig. 12.

The findings as regards the relation between final heart rate and duration of work showed good correspondence within both of the subject groups investigated.

In summary the present results indicate that a constant or nearly constant final pulse level is first attained after maximal work periods exceeding 6

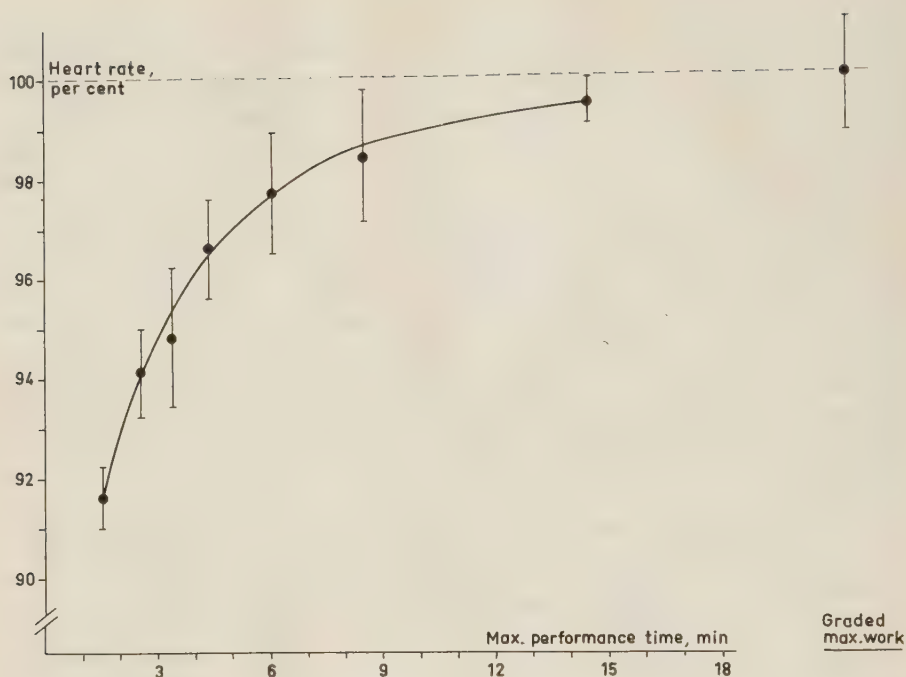


Fig. 12. Final heart rates after exhausting work of varying duration in 28 civilian volunteers

The values are given as a percentage of the heart rate attained after graded maximal work. Symbols denote $\bar{x} \pm s_{\bar{x}}$.

minutes. In performances of longer duration also a slightly higher heart rate was observed. The differences were, however, small and statistically insignificant.

Peak oxygen uptake and maximal pulmonary ventilation in exhausting work of varying duration

The above-mentioned findings of divergent final heart rates after maximal performances of different duration encouraged an extension of the experimental series to include determinations of maximal oxygen uptake.

In 9 individuals (Series F₁) the peak oxygen uptake was determined during maximal work periods of varying intensity. After initial assessment of the maximal working capacity, the subjects had to participate in two or more additional performances. In these the work loads were chosen to give alternatively short or long maximal work periods. To avoid the influence of accidental training effects, here too the sequence of work loads was varied.

During each work period the heart rate was continuously recorded by Ecg and the maximal oxygen uptake determined by the Douglas bag method. For technical details regarding the determination of maximal oxygen uptake, see page 61.

In each individual the peak oxygen uptake was compared for exhausting performances of shorter and longer duration. In some cases means of two determinations were utilized. The results appear in Fig. 13.

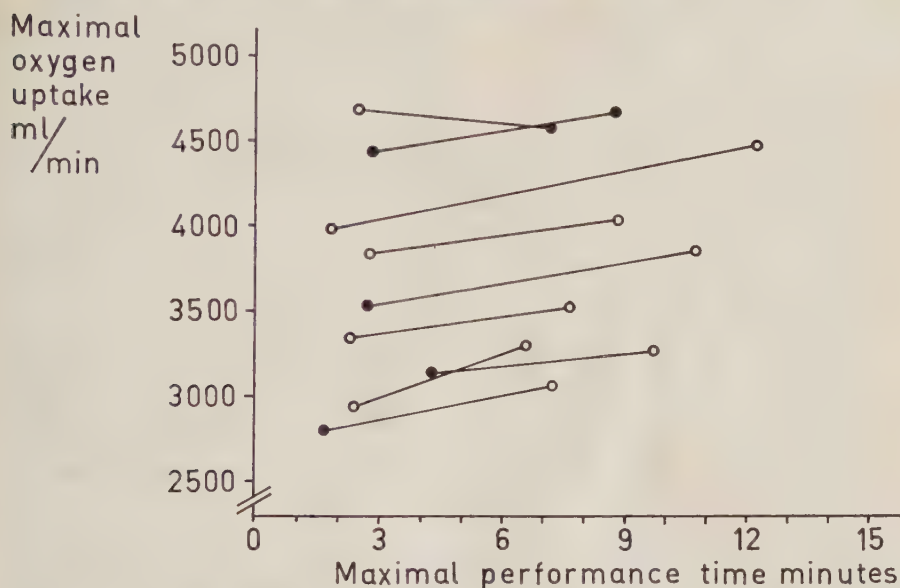


Fig. 13. Maximal oxygen uptake during exhausting work of varying duration

Series F: civilian volunteers. $n = 9$

Unfilled circles denote experimental values from one maximal performance. Filled symbols denote mean values from two maximal performances with the same or almost the same relative work load.

As shown, higher values were on average attained in exhausting performances of longer duration than in those of shorter duration. Comparison between mean maximal oxygen volumes corresponding to average work durations of 2' 39" and 8' 46" thus showed a statistically significant difference ($\bar{x}_1 = 3,628$, $\bar{x}_2 = 3,863$; $\text{diff.} = 235 \text{ ml/min. } P = 0.01-0.001^{**}$).

Similarly the maximal pulmonary ventilation was compared for work periods of varying duration. The results are given in Fig. 14.

Here, too, higher values were recorded after longer performances. The difference between ventilation volumes corresponding to work durations of 2' 39" and 8' 46" was, however, not statistically significant ($\bar{x}_1 = 99.76$, $\bar{x}_2 = 108.11$; $\text{diff.} = 8.35 \text{ l/min. } P = 0.1-0.05$).

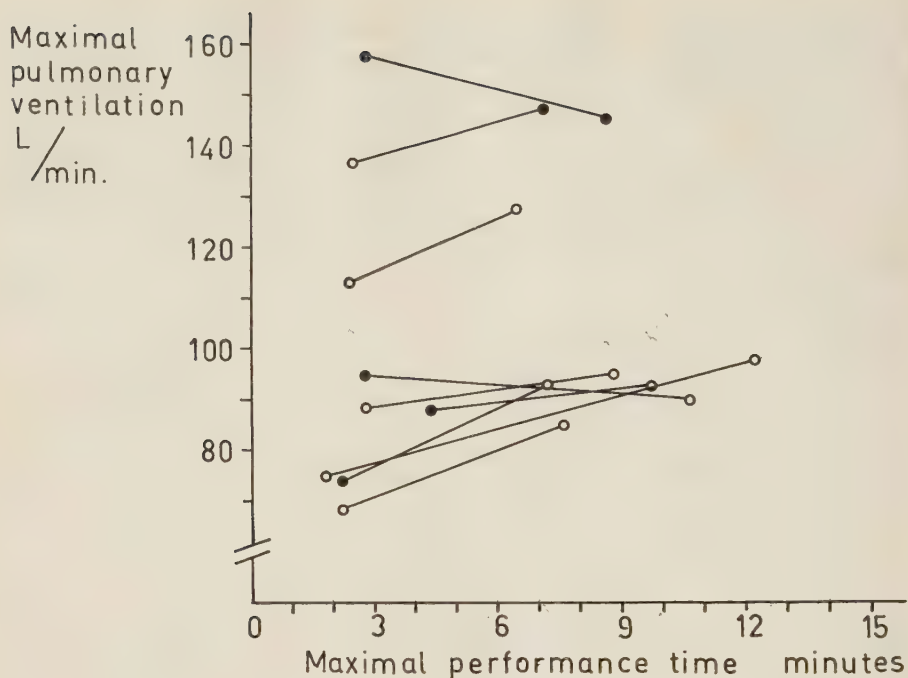


Fig. 14. Maximal pulmonary ventilation during exhausting work of varying duration

Series F: civilian volunteers. $n = 9$

Unfilled circles denote experimental values from one maximal performance. Filled symbols denote mean values from two maximal performances with the same or almost the same relative work load.

Final concentration of lactic acid after exhausting work of varying duration

To estimate the degree of anaerobic work in exhausting performances of varying duration, the final lactic-acid concentration in blood was determined in two groups of subjects. These investigations were carried out in close connection with the above-mentioned studies on final heart rate. In all cases the blood samples were taken during the first few seconds after termination of the maximal work.

One group consisted of ordinary conscripts (Series D), whereas the other group was composed of civilian volunteers (Series F). The work load was chosen to give maximal performances of varying duration. For Series D the final lactic-acid concentration was determined in 37 individuals, each participating in one maximal performance. For Series F, sampling was performed

in 21 individuals each participating in several performances—number of determinations: 80. After the graded maximal test samples were secured from 37 subjects in Series D and 16 subjects in Series F. The results are given in Fig. 15.

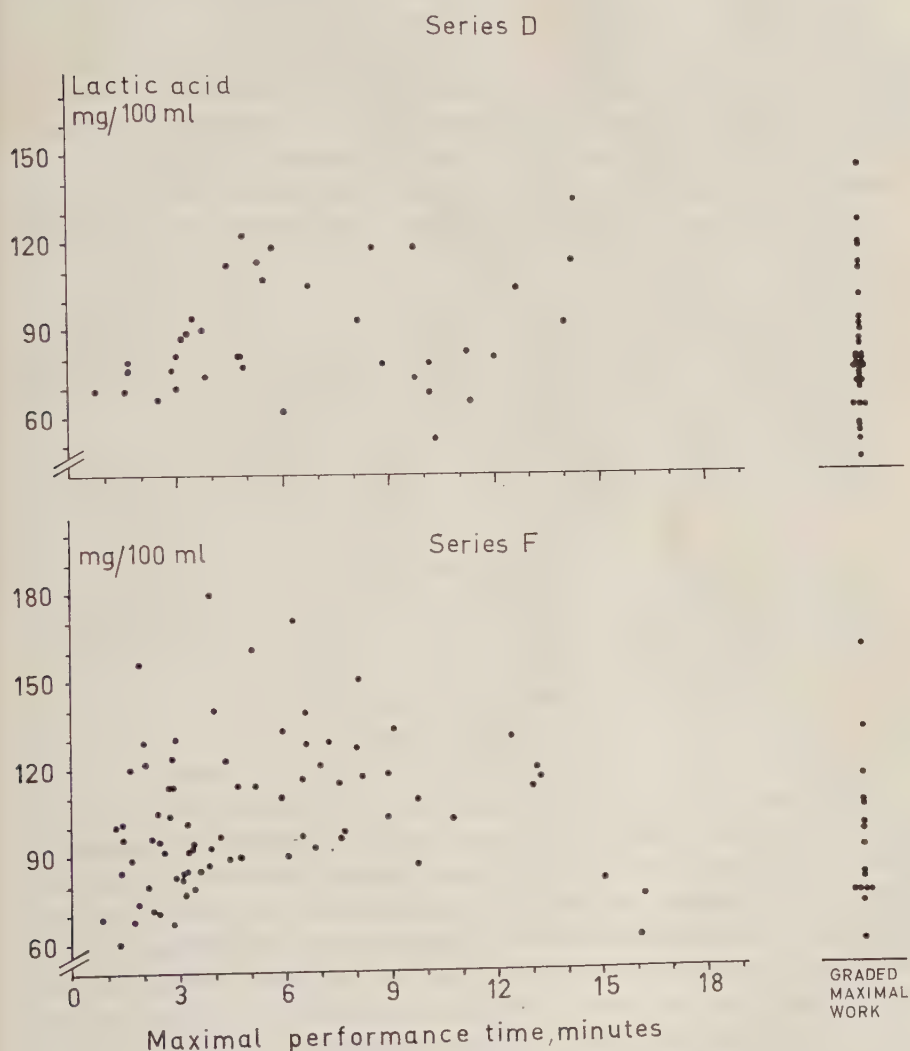


Fig. 15. Final lactic-acid concentration after exhausting work of varying duration in a group of 19/20-year-old conscripts (D) and in a group of civilian volunteers (F)

The work loads were chosen to give maximal performances of a duration between about 1 and 18 minutes. In addition the final lactic-acid concentrations are set out for exhausting work with work loads increased stepwise.

As can be seen, the final lactic-acid concentrations show a considerable scattering between high and low values in both subject groups investigated. For short, intensive performances as well as longer, easier ones a considerable elevation of lactic-acid concentrations was observed as compared with the levels generally recorded at rest.

A comparison between the concentrations after exhausting performances of varying duration showed similar differences within both experimental groups. The highest mean value was found after performances of a duration approximating 10 minutes. For shorter as well as longer work periods lower mean values were recorded. The differences observed were, however, not statistically significant in any of the subject groups investigated.

In Table 12 mean intraindividual differences are given for three partially overlapping subgroups of Series F (k—m).

Table 12 Final lactic-acid concentrations in Series F divided into subgroups

Subgroup	n	Maximal performance time			Mean lactic acid. conc. mg/100 ml	Diff. mg/100 ml	P
		Range	Mean value	time			
		Min.	Min.	sec.			
k	11	0—3	1	53	95.7	+ 11.1	0.3—0.2
		3—6	4	18	106.8		
l	12	3—6	4	02	101.0	+ 7.4	0.4—0.3
		6—18	10	49	108.4		
m	14	6—18	9	29	106.8	— 11.5	0.1—0.05
		19—34†	27	25	95.3		

† Graded maximal work.

Discussion

Final heart rate. The magnitude of cardiac output is determined by the stroke volume on the one hand and the heart rate on the other. The changes in cardiac output during adaptation to work are mainly due to the increased heart rate, the augmentation of stroke volume being less pronounced. The latter seems predominantly to occur during work in the sitting position, being confined to the period shortly after the commencement of exercise. The mechanism of this increase has been explained by a redistribution of blood from the leg vasculature to the central circulation (2, 19, 70, 84, 116).

In the studies reported, the final heart rate was found to be on average lower in short periods of exhausting work than in performances of longer duration. If the stroke volume is assumed to be the same in both events the observations made in the present study may have the following significance.

During work at high intensities the cardiac output may not reach the same magnitude as during performances with lower loads. Especially when maximal working time is reduced below 3 minutes, the highest attainable cardiac output seems to decrease significantly. At these high work loads the central circulatory capacity is evidently not used to its full extent.

Peak oxygen uptake and maximal pulmonary ventilation. The level of oxygen uptake during physical exercise is a function of several mutually interrelated factors, including pulmonary ventilation, alveolar gas exchange, cardiac output, peripheral circulatory adjustment and arteriovenous difference. As has been shown by a number of investigators, the metabolic rate during "steady state" work is roughly linearly correlated with the heart rate (29, 129). Furthermore, in studies using catheterization technique, a high correlation has been established between oxygen consumption on the one hand and cardiac output as well as oxygen utilization on the other (70). For pulmonary ventilation, also, a similar although—especially in work of high intensities—less pronounced connection with oxygen uptake has been noted (7).

Of the factors mentioned, the cardiac output seems to be the most important component function determining the magnitude of oxygen consumption during physical exercise (97).

As mentioned, a higher oxygen uptake was observed in more lengthy exhausting work (mean performance time 8 minutes and 46 seconds) than in shorter periods (mean performance time 2 minutes and 39 seconds).

In the interpretation of results the close association between oxygen supply and circulatory functions has to be taken into account. The final heart rate and the peak oxygen uptake may both approximately reflect the magnitude of cardiac output attained during exhausting work. The present results would thus seem to support the conclusions drawn from the studies of final heart rate.

Besides the function of oxygen-transporting organs the degree of peripheral oxygen utilization may, however, also influence the magnitude of oxygen uptake. An increased oxygen extraction in the muscles would here theoretically be able to compensate for the incomplete adaptation of the central circulation. On the other hand, the present results do not support the hypothesis that such compensatory mechanisms exist.

In summary, the studies reported suggest that in maximal performances of short duration the oxygen-supply capacity is generally not fully utilized. The probable explanation for this seems to be that the time of work may be too short for maximal circulatory adjustment.

Final lactic-acid concentration. In earlier studies of exhausting performances the lactic-acid concentration has been used as an approximate measure of anaerobic work. The basis for these estimations has been the relation between oxygen debt and lactic-acid formation (11, 16, 37, 44, 64, 79). In the present investigation it was considered to be of interest to compare the degree of anaerobic work in exhausting work of varying duration.

In two subject groups studied in this respect the lactic-acid concentration was measured in finger-prick blood immediately after the conclusion of the maximal work. A large scattering of values as well as moderate disparities were established for final lactic acid after exhausting performances of varying duration. The differences were, however, not statistically significant in either of the groups.

In evaluating the results it should be remembered that besides muscular hypoxia several other factors, such as forced hyperventilation and elevated pyruvate concentration, may influence the lactic-acid levels (72, 73). This may account for the large intra- as well as interindividual variation observed. Furthermore in the performances of short duration the values recorded may be somewhat too low, owing to the lag of circulation from the muscles to the sampling site. If the sampling is delayed, however, another error will be induced, viz. metabolism of lactic acid by the resting muscles after work.

Even if these possible errors are taken into consideration, the present results seem to indicate that the degree of anaerobic work will be of about the same order of magnitude in exhausting performances of varying duration (between about 1 and 25 minutes).

From the present findings it may be suggested that the following sequence of events occurs in maximal exertions of varying duration. In exhausting work with high work loads lasting for 2—3 minutes the large energy demands of the muscles will only to a small extent be met by the oxygen available; anaerobic mechanisms have to provide the greater part of the energy supply. During the course of the work, a concentration of anaerobic metabolites will rapidly accumulate, leading to a termination of work before maximal circulatory adaptation is attained. If, on the other hand, the load is put lower, allowing the work to continue for, e.g., 6—10 minutes, the energy demands of the working muscles will be more moderate. The oxygen supplied by the circulatory system will be able to balance the energy demands more effectively. As the work continues, however, anaerobic metabolism will here, too, give rise to an accumulation of metabolic products, although at a more gradual rate. The interval before termination of work is provoked will apparently be sufficiently long for practically maximal adjustment of the circulatory system to occur.

The highest attainable oxygen uptake, heart rate and lactic-acid concentration after exhausting work of varying duration has earlier been studied by Åstrand & Saltin (13). Each performance was here preceded by a 10-minutes period of "warming up", using a work intensity corresponding to 55 % of the maximal oxygen uptake. No significant differences were found for maximal oxygen uptake and heart rate if the length of work on the highest load was varied between 1 and 8 minutes. Similar results were obtained for maximal lactic-acid concentration, whereas ventilatory volumes showed significantly higher values after the short heavy performances.

In the study just cited the purpose of investigation as well as the design of the experiments differed in essential respects from those of the present study. The preliminary exercise may have contributed to a better circulatory adjustment in performances of high intensity than was attained in the present investigation, where work was initiated directly with a high work load. This may account for the disparity of results. Other factors, such as divergence in the physical condition of the material, may also be of importance in explaining the discrepancy.

Maximal physical performances in different civilian and military subject groups with special regard to final heart rates and lactic-acid concentrations attained

As pointed out above, divergent final pulse levels may be attained in physical exertions of different kinds. The concept of maximal pulse should therefore not be used without definition of the type of exercise as well as the length of work.

Besides intraindividual variations according to the character of the work, considerable interindividual differences are encountered. At present, not all the factors determining the individual level are known. However, psychological mechanisms, above all the motivation, may be assumed to play an important role in limiting maximal performances. Motivation is here defined as the willingness of the subject to perform physical work until complete exhaustion.

To elucidate the importance of the individual attitude, some results of earlier investigators are summarized. In the present study different subject groups with divergent psychological conditions are also studied in this respect.

In Table 13 nine studies, quoted from the literature, are compared in regard to character of material, size of subject group, age, type of work, maximal heart rate and lactic-acid concentration. As can be seen, the composition of the material varies from one study to another. Mostly the subjects are college students or military candidates. Both in regard to physical capacity and desire to do well these may be assumed to surpass ordinary individuals. As a rule they exhibit high values of maximal heart rate as well as of lactic-acid concentration after maximal exertions. Comparison with subject groups of more average composition shows, that the latter generally have lower final levels (cf. refs. 9 and 11 B).

In the present investigation four subject groups were studied in regard to pulse rate, recorded immediately after exhausting performances. Two of them were conscript groups ordered to undergo examination, one group consisting of non-selected individuals (Series D), the other being selected at random (Series B₁). A third group was composed of military volunteers (Series E) and a fourth consisted of civilian volunteers (Series F).

Table 13 Final heart rate and lactic-acid concentration after exhausting work

Reference No.	Author	Category	n	Age	Type of work	Maximal heart rate beats/min.	Maximal lactic acid mg/100 ml
40	Dill, D. B. & Brouha, L.	men	14	20—36	running on treadmill	195	—
109	Robinson, S.	men	11	20—29	running on treadmill	189	89
96	Metheny, E. L. <i>et al.</i>	college men	30	19—23	running on treadmill	194	119
26	Brouha, L. & Heath, C.	college men	176	17—22	running on treadmill	193	—
30	Christensen, E. & Högberg, P.	school boys	21	14—16	skiing 5 km	237	—
11 A	Åstrand, P.-O.	college men	42	20—33	running on treadmill and cycling	194	112
B	»	college women	44	20—25	running on treadmill and cycling	198	103
118	Slonim, N. B. Gillispie, D. & Harold, W.	naval aviation cadets	50	18—25	running on treadmill	188	—
123	Döbeln, W. v., Engström, C.-G.	pilot candidates	21	18	cycling	204	107
	Malmström, G. & Ström, G.	pilots	21	40	cycling	185	108
9	Åstrand, I.	women, mostly house-wives	8	20—29	cycling	187	121

As shown above, the level of final heart rate after exhausting effort is partly dependent upon the duration of work. When comparing maximal heart rates in different subject groups, therefore, the length of performance has to be taken into consideration. In Fig. 16 final pulse rates in different series after equivalent work were compared.

It was here found that for short as well as longer exhausting performances—at least for durations below $\frac{1}{2}$ hour—the volunteers tended to reach higher final pulse levels than did average conscripts.

For one of the subject groups, viz. Series E, the graded work test could not be applied, because the examinees could be available only during

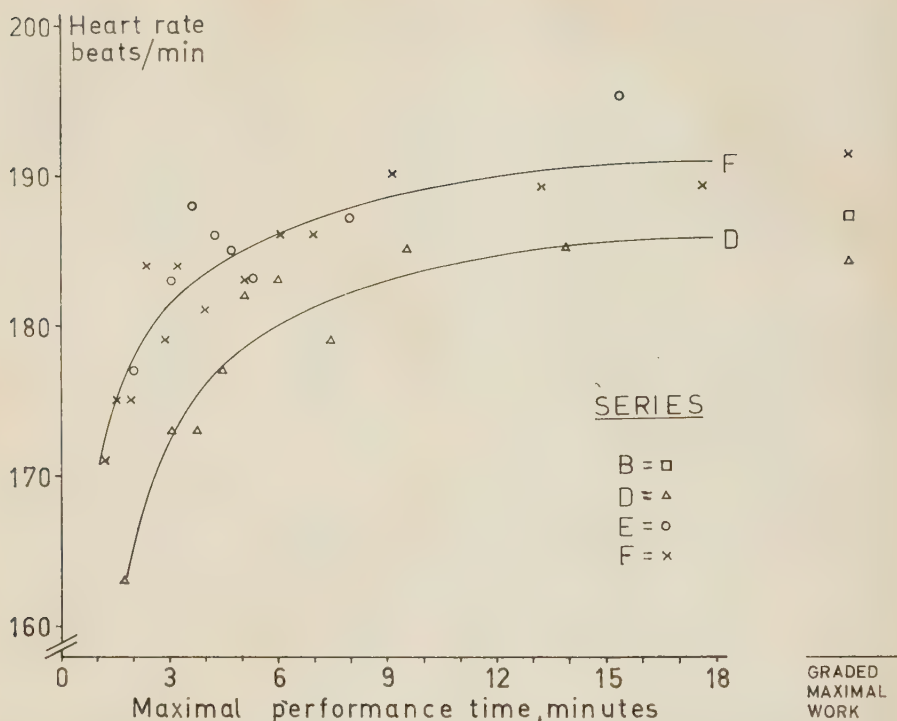


Fig. 16. Final heart rates after exhausting work of varying duration. A comparison of maximal heart rate in subject groups of different composition

Series B (□) = randomly selected conscripts

» D (△) = non-selected conscripts

» E (○) = military volunteers

» F (×) = civilian volunteers

For subject groups D, E and F the symbols in the left part of the diagram represent means of 10 experimental values. The resulting curves are drawn freehand for Series D and E. The symbols on the right denote means of whole subject groups, expressing average final pulse after graded maximal work.

two days, used for duplicate maximal tests with constant work loads. Here final pulse values are compared with those of Series D, in both cases after exhausting performances with a mean duration of 3 minutes and 55 seconds. It was found that the volunteers attained a significantly higher heart rate than did the ordinary conscripts. The difference of comparable maximal pulse frequencies was found to be statistically highly significant ($n_D = 55$, $n_E = 60$. Maximal performance time: range 0—6 min., mean value 3 minutes 55 seconds. Final pulse values: $\bar{x}_D = 174$, $\bar{x}_E = 184$; *diff.* = 10 beats/min P^{***}).

The final heart rate after the graded work test, performed until exhaustion, was furthermore compared between Series F (civilian volunteers) and Series D (ordinary conscripts). Here, too, the voluntary subjects showed higher pulse values than did the individuals ordered to undergo examination ($\bar{x}_D = 184.4$, $\bar{x}_F = 191.2$; *diff.* = 6.8 beats/min P^{**}). For Series F compared with Series B₁ (randomly selected conscripts) the difference was probably significant ($\bar{x}_B = 186.5$, $\bar{x}_F = 191.2$; *diff.* = 4.7 beats/min P^*).

Between the two conscript groups exhibiting a similar psychological attitude, no significant difference was found as regards maximal heart rates.

Besides final heart frequency some other biological data were compared between the different categories investigated. As regards age, the civilian volunteers were on average six years older than the military conscripts. They were furthermore somewhat heavier and revealed significantly higher values of estimated subcutaneous fat than members of the other groups. The PWC_{170} was of about the same magnitude as for the conscripts. The values of maximal working capacity (PWC_{max} 6') were, however, slightly higher than for the men ordered to undergo examination (*Diff.* P^*). A higher maximal physical working capacity was similarly established for the military volunteers as compared with the ordinary conscripts (*Diff.* P^*). See Table 1. As far as recorded data are concerned, no other significant differences were observed.

A comparison of the present results with those cited from the literature was furthermore performed. With reservation for differences in respect of investigational techniques, the maximal pulse of randomly selected conscripts seems to be of the same order of magnitude as for the subjects investigated by, for instance, Slonim *et al.* (118). Compared with other, mostly voluntary subject groups, the final heart rate appeared to be lower, at least for this type of work.

Besides maximal heart frequency, the lactic-acid concentration was determined in two groups of subjects, viz. Series D (ordinary conscripts) and Series F (civilian volunteers). Since no significant differences were found in concentrations after exhausting performances of varying duration, means were computed for all final lactic-acid values of the separate groups. The volunteers here showed a significantly higher average concentration after maximal work than did the ordinary conscripts ($\bar{x}_D = 84.4$ $\bar{x}_F = 105.9$; *diff.* = 21.1 mg per 100 ml. $P < 0.001^{***}$).

Discussion. Four subject groups of different composition were investigated in the present study. Military groups of ordinary conscripts as well as individuals with a pronounced interest in high test results were examined. In

addition, one civilian group was studied, representing a selection of people with a high degree of motivation.

Subject groups selected at random—as for instance the military conscripts in Series B₁—may *a priori* be assumed to contain individuals with a variety of attitudes to physical exertion. Compared with volunteers they cannot on average be expected to have the same degree of motivation.

In the present study, factors other than the natural willingness to participate in exhausting work were as far as possible reduced. Thus all the conscripts were informed about the scientific purposes of the investigation, as described on page 48.

As mentioned, a higher mean final heart rate was observed in the group of civilian volunteers than in the two groups of ordinary conscripts. According to the findings of earlier investigators the maximal heart frequency generally decreases with advancing age (9, 109). Thus a slightly lower value would have been expected instead. The discrepancy regarding weight and estimated subcutaneous fat was rather small and probably cannot be related to the circulatory data discussed.

The two groups of ordinary conscripts on the one hand and the military and civilian volunteers on the other were selected in different ways. As the different motivation seemed to be the dominating factor separating these two categories of examinees, this quality may reasonably be connected with the disparity in final heart rates.

The finding of a generally higher final lactic-acid level in the group of civilian volunteers than in the conscripts would indicate that the former were able to contract a larger oxygen debt than were the conscripts. Here again the difference of psychological attitude may account for the discrepancy.

In the subject groups reported on by earlier investigators, the values of lactic acid observed at the end of exhausting work were generally higher than those recorded in the present series. It may be pointed out that the actual levels were found in samples taken immediately after the termination of work, whereas the values of earlier authors as a rule represent maximal concentrations, reached 3—5 minutes after termination of work. This may explain the differences observed.

Comparisons between groups of subjects thus strongly suggested that there is a close connection between the height of final heart rate and lactic-acid concentration after exhausting work on the one hand and motivation on the other.

For single individuals, however, it was not possible to draw any definite conclusions regarding the association between the physiological and psycholog-

ical characteristics mentioned. A reliable criterion of the individual motivation would seem to be one important prerequisite for correlation studies of this kind. It is possible that psychological investigations will be able further to elucidate the association between final heart rate and lactic-acid concentration after strenuous work on the one hand and motivation on the other.

Relation between different methods for assessment of physical capability

To establish the significance of different expressions of physical working capacity the present results were related to those of some other methods.

Investigations were carried out in which, besides maximal physical working capacity ($PWC_{\max}$), the working capacity at a pulse of 170 (PWC_{170}) and maximal oxygen uptake ($\dot{V}O_{2\max}$) were determined. The latter was defined as the peak oxygen uptake attained during exhausting work of sufficient duration to give a maximal circulatory adaptation.

The material used consisted of the group of civilian volunteers described earlier (Series F) and the two groups of ordinary non-selected conscripts (Series C and D). The determinations of $\dot{V}O_{2\max}$ were performed in 9 members of the voluntary group (Series F₁).

In Series F the time load curve was established for each individual. From the regression equation different expressions of the maximal working capacity were calculated according to the duration of work. In the conscript groups the capacity corresponding to a maximal performance time of 6 minutes was estimated by intra- or extrapolation from two or occasionally three experimental values ($PWC_{\max 6'}$).

The above-mentioned expressions of maximal working capacity were studied in relation to PWC_{170} and partly also to $\dot{V}O_{2\max}$. The results of these correlation studies appear in Tables 14 A and B.

For one of the two subject groups composed of non-selected military conscripts (Series D) the scatter diagram below shows regression line as well as standard error of estimate. See Fig. 17.

In two of the groups investigated (C and F) the maximal voluntary iso-

Table 14 A. Relationship between $PWC_{\max 6'}$ (x) and PWC_{170} (y)

Series	n	r	P	Equation of regression line	s_e
C	58	0.67	***	$y = 0.589 x + 293$	118
D	52	0.72	***	$y = 0.595 x + 243$	134
F	28	0.49	**	$y = 0.372 x + 523$	148

Note: Values are given in kpm/min.

Table 14 B Correlation between $PWC_{\max} (x)$ and $PWC (y) \dot{V}O_{2\max} (y)$

Series	Determination	$PWC_{\max 1'}$	$PWC_{\max 3'}$	$PWC_{\max 6'}$	$PWC_{\max 10'}$	$PWC_{\max 15'}$
F_1	$\dot{V}O_{2\max}$	$r = 0.83^{***}$	$r = 0.91^{***}$	$r = 0.94^{***}$	$r = 0.95^{***}$	$r = 0.95^{***}$
$n = 9$	$\bar{y} = 3,874$	$s_e = 381$	$s_e = 237$	$s_e = 237$	$s_e = 216$	$s_e = 207$
F	PWC_{170}	$r = 0.39^*$	$r = 0.46^*$	$r = 0.49^{**}$	$r = 0.50^{**}$	$r = 0.49^{**}$
$n = 28$	$\bar{y} = 1,086$	$s_e = 156$	$s_e = 151$	$s_e = 148$	$s_e = 147$	$s_e = 148$

Note: r = correlation coefficient, s_e = standard deviation of residuals. Figures of $\dot{V}O_{2\max}$ are given in ml/min, values of PWC_{170} are given in kpm/min.

metric strength was recorded with the aid of the strain-gauge method described earlier. As an expression of general muscle strength there was here used the standardized muscle factor according to the definition reported

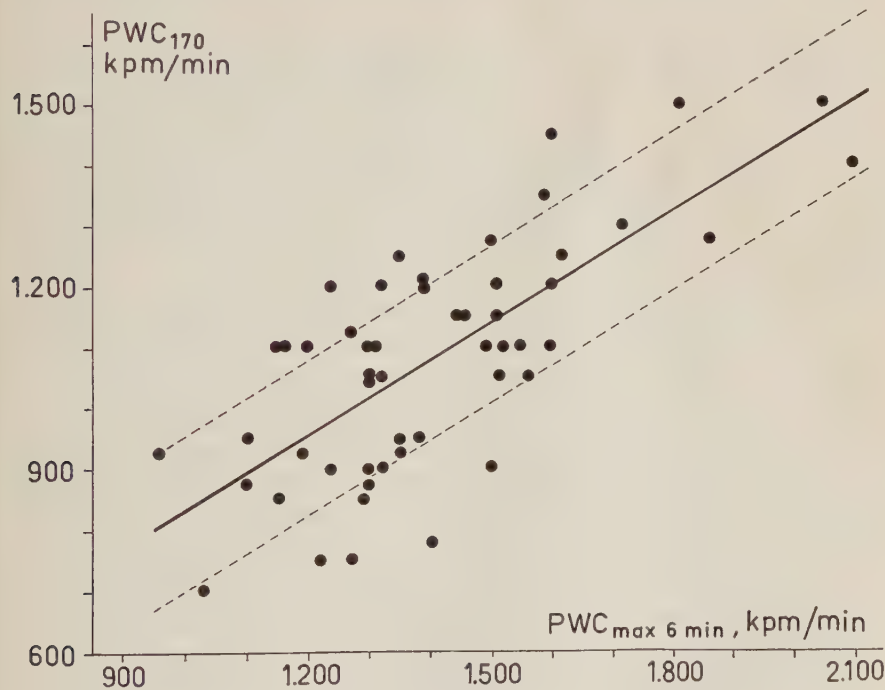


Fig 17. Correlation between $PWC_{\max 6'}$ and PWC_{170}

Series D $n = 52$
Scatter diagram illustrating the relation between the working intensity sustainable during a maximum of 6 minutes and the working intensity at pulse 170 in circulatory steady state. Broken lines denote $\pm$ standard error of estimate.

on page 41. For calculation of the muscle factor of the participating individuals the mean values as well as standard deviations from the corresponding series were used.

The results of correlation studies between $PWC_{\max}$ and PWC_{170} on the one hand and the muscle factor on the other are shown in Table 15.

Table 15. Correlation between PWC and muscle strength (standardized muscle factor)

Series	$PWC_{\max 1'}$	$PWC_{\max 3'}$	$PWC_{\max 6'}$	$PWC_{\max 10'}$	$PWC_{\max 15'}$	PWC_{170}
F						
$n = 27$	$r = 0.60^{***}$	$r = 0.69^{***}$	$r = 0.69^{***}$	$r = 0.68^{***}$	$r = 0.65^{***}$	$r = 0.46^*$
C						
$n = 56-58$	—	—	$r = 0.34^*$	—	—	$r = 0.19$

Note: r = correlation coefficient.

Discussion. As shown above, the correlation between $PWC_{\max 6'}$ and $\dot{V}O_{2\max}$ was remarkably high. The strong association between these two expressions of physical working capacity may perhaps be sought in the fact that both are estimated from results of maximal performances. With reservation for the small size of the material investigated the close correspondence between these methods may justify an interchangeable use of the techniques mentioned.

The submaximal test of Karolinska Sjukhuset, in which the work intensity is determined in relation to the pulse of 170 in relative circulatory steady state, seems to afford an objective test of physical working capacity. In studies using the results from ski-running as a criterion of endurance, a high correlation with PWC_{170} was found in a group of military conscripts (24). The character of this method makes it especially suitable for objective evaluation of the capacity of the oxygen-transporting system, whereas in maximal tests other factors as well may influence the results.

It was therefore considered to be of great interest to study in what degree maximal tests of physical working capacity might give information about the PWC_{170} of the individual and vice versa.

In one civilian and two military subject groups statistically significant correlations were found between $PWC_{\max 6'}$ and PWC_{170} . The degree of correlation showed moderate differences from category to category. Neither of the military groups was randomly selected, and consequently they were not strictly representative of the population studied. As they were composed

of average conscripts, some conclusions may however be drawn regarding the possibilities of prediction from one method to the other.

Thus it appears that in ordinary conscripts the PWC_{170} may be predicted from $PWC_{\max 6'}$ with an error of about 12 % (the standard error of estimate in Series C was 10.7 %, in Series D it was 12.4 % of the mean value).

In this part of the study were also included correlations between $PWC_{\max}$ defined in different ways, and PWC_{170} as well as $\dot{V}_{O_{2\max}}$. It was found that the capacity for short heavy work correlated somewhat lower with both PWC_{170} and $\dot{V}_{O_{2\max}}$ than did the capacity for longer work. This observation may accord with the above-suggested hypothesis of an incomplete circulatory adaptation in exhausting performances of a shorter duration than 6 minutes.

The investigations on maximal voluntary isometric strength indicated that the correlation is of about the same degree between strength and the different expressions for maximal work capacity studied. Obviously the muscle strength may be about equally important in both shorter and longer maximal performances in the duration range 1—15 minutes—at least in highly motivated individuals. Between muscle strength and the physical working capacity at a pulse of 170, however, the correlation was lower. The latter observation was made in both series investigated.

The correlation found between $PWC_{\max 6'}$ on the one hand and PWC_{170} on the other was differently high in average conscripts and civilian volunteers. This was also the case for the correlation between $PWC_{\max 6'}$ and muscle strength, although in the opposite direction. Here it seems that the volunteers were using a greater part of their muscle strength in the maximal test ($PWC_{\max 6'}$) than were the ordinary subjects. In the latter, however, the cardiopulmonary function was presumably more decisive for the results obtained.

In clinical application submaximal tests may be the only choice in evaluation of the physical working capacity. The value obtained will here reflect especially the cardio-circulatory capacity. On the other hand when a maximal test can be used it will in addition give information regarding the muscle strength and subjective motivation of the individuals. In physical classification, for example in selection of military personnel, this may not involve any disadvantage, as the latter quality is one important aspect of individual fitness for military use. The latter assumption is valid only provided that the motivation at the time of examination corresponds to that in the service concerned.

Summary and conclusions

Some problems pertinent to the assessment of maximal isometric muscle strength and physical working capacity were investigated.

To establish the relation between the strength of single muscle groups, the muscle force in different parts of the body had to be determined. For this purpose a method was designed whereby isometric strength could be measured in 22 mainly large muscle groups.

The maximal contractile force was evaluated for attempted movements, using certain well-defined positions. For adjustment of positions and for fixation a stand in the shape of a chair was used. A set of strain-gauge dynamometers attached to the chair were connected to a central recording instrument containing a measuring bridge and an alternating current amplifier. The values were read directly in kiloponds, according to prior calibration.

The technique was evaluated in regard to instrumental and biological errors. Reproducibility was established for different phases of testing.

The significance of strength evaluation with different methods was furthermore discussed.

The method was applied to the study of the muscle strength patterns in military conscripts, civilian volunteers and two categories of élite athletes.

In one conscript group the interrelationship of muscle strength was studied for different parts of the body. On average the correlation between single muscle groups was high. Certain muscles, however, were judged to be preferable in short tests of strength. Reproducibility as well as accessibility for measuring had, here also to be taken into consideration.

A group of conscripts was followed during the nine months of basic military service. Changes of muscle strength were found to be small and heterogeneous. In part they could be ascribed to the effect of physical training during military service; but they may also have been partly due to the fading of civilian environmental influences. This was the case with the physical working capacity as well (PWC_{170}). The relative constancy of muscle strength, however, may indicate that the muscular demands of military service will on the whole correspond to those of average civilian life.

During the observation period the body height was stationary, the body weight increased and the estimated subcutaneous fat decreased. The significance of these findings is discussed in relation to those of earlier investigators.

In the second part of the experimental study some problems connected with the evaluation of maximal physical working capacity were investigated.

A method earlier described by Grosse-Lordemann & Müller was applied. The relationship between work intensity and maximal performance time, suggested by these authors, was confirmed in the present investigation.

The reproducibility of maximal physical work was tested in a group of military conscripts taking part in duplicate performances on separate days. For each time value the work intensity corresponding to a maximal performance time of 6 minutes was estimated. The maximal working capacity, expressed in this way, showed a variation of 4.1 % of the mean value.

As one aspect of maximal working capacity the circulatory adaptation was studied in exhausting work of varying duration. The final heart rate and the peak oxygen uptake measured in exhausting work of short duration (2—3 minutes) were found to be significantly lower than the levels attained in longer maximal performances (6—10 minutes). For final lactic-acid concentration no statistically significant differences were established. The results seem to indicate that the circulatory capacity is not completely utilized in strenuous work of short duration. It is only in exhausting performances lasting for more than 6 minutes that the circulatory adaptation may be maximal or nearly maximal. The studies on final lactic acid may suggest that the oxygen debt contracted will be of about the same order of magnitude in maximal performances lasting between about 1 and 25 minutes.

Groups of volunteers were found to reach on average higher final heart rates and lactic-acid concentrations than did groups of ordinary conscripts. The significance of these observations is discussed in relation to results reported by earlier investigators.

A comparative study was performed of expressions of maximal working capacity ($PWC_{\max}$) on the one hand and maximal oxygen uptake ($\dot{V}_{O_2\max}$) and the physical working capacity at a pulse of 170 (PWC_{170}) on the other. The correlation between $PWC_{\max}$ and $\dot{V}_{O_2\max}$ was remarkably high, a finding explained by their common character of maximal tests. Between $PWC_{\max}$ and PWC_{170} a statistically significant, although lower, correlation was found. This may be ascribed to the fact that these two measures probably reflect different aspects of physical working capacity. Whereas the PWC_{170} will give an objective value of the capacity of the oxygen-transporting system, the $PWC_{\max}$ will also contain an element of motivation and muscular strength. With reservation for the representativity of the material investigated, prediction of PWC_{170} from $PWC_{\max}$ seems to involve an error of about 12 % in ordinary conscript groups.

For maximal voluntary isometric muscle strength the correlation with different expressions of physical working capacity was studied and the possible significance of findings is discussed.

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